VOL. 249 MARCH 1951 No. 3

American Journal of Science

Established in 1818 by Benjamin Silliman

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Published monthly. Eight dollars a year. Seventy-five cents a copy.
Foreign, eight dollars sixty cents. Canada, eight dollars thirty-five cents.

AMERICAN JOURNAL OF SCIENCE

Established in 1818 by Benjamin Silliman

THE FIRST SCIENTIFIC JOURNAL IN THE UNITED STATES

DEVOTED TO THE GEOLOGICAL SCIENCES AND TO RELATED FIELDS

Editor: Chester Ray Longwell
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Entered as second-class matter at the Post Office at New Haven, Conn., under the Act of March 3, 1879. Published monthly at Sterling Tower, Yale University, New Haven, Conn.

Subscription rate $8 per year (75 cents a number). Student rate $5 per year (application blanks available on request). Postage prepaid to the United States and Central and South America; 35 cents per year to Canada; 60 cents per year elsewhere.

The Journal completed its *first* series of 50 volumes in 1845, its *second* series of 50 volumes in 1870, its *third* series of 50 volumes in 1895, its *fourth* series of 50 volumes in 1920, its *fifth* series of 36 volumes in 1938. Since 1938 the numbering by series has been discontinued, and volumes are annual and bear the whole numbers as of 1818, that for 1939 being volume 237.

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Reference

Lane, B. H., 1935. Suggestions to authors of papers submitted for publication by the United States Geological Survey: U. S. Geol. Survey, Washington, D. C. (For sale by Superintendent of Documents, Washington, D. C., 5¢.)

[American Journal of Science, Vol. 249, March, 1951, Pp. 177-207]

American Journal of Science

MARCH 1951

LATE-GLACIAL AND POSTGLACIAL POLLEN DIAGRAMS FROM MAINE

EDWARD S. DEEVEY, JR.

ABSTRACT. Pollen diagrams from three lakes and one bog in northern Aroostook County, Maine, have shown for the first time in North America that the "postglacial" advance of forests was preceded by a "late-glacial" time characterized by tundra climate. The older time corresponds in every essential respect with the late-glacial phase of northern Europe: non-arboreal vegetation, dominated by grasses and sedges, but including *Artemisia* (?) and many other herbaceous types, contributed several hundred per cent of the arboreal pollen, all of which is considered to have been wind-borne from a great distance. Resemblance to the standard European sections is enhanced by the occurrence, within the "late-glacial" segment, of a zone having considerably less non-arboreal pollen than the zones above and below and involving the intercalation of a band of marl within clay sediments. This middle zone, called *L 2*, is strikingly like the Allerød oscillation of Goti-glacial age and by analogy may date from the Cary-Mankato interval. There are reasons for believing that the tundra phase underlies the organic sediments in Connecticut and probably elsewhere, but as the author suggested in 1949, "geologic circumstances and the mental habits of pollen workers may have conspired to make them miss it."

The postglacial parts of the diagrams are sufficiently normal for New England to permit their correlation with the standard section for eastern North America, though there are many peculiarities, such as the absence of hickory and chestnut pollen and the subordination of oak to pine, hemlock, and birch. These peculiarities reinforce the resemblance to European diagrams, and the sequence from northern Maine is astonishingly similar to that from the more continental parts of Scandinavia. Table 2 gives a summary of the zonation and its probable correlation with the European section.

Two lakes in Kennebec County, about 175 miles SSW of the Aroostook County localities, were also investigated, but the diagrams are much more like those of southern New England, and neither shows "late-glacial" zones. The reasons are apparent, and different in the two cases: in one the organic sediment lies unconformably on marine clay, which so far has proved barren of pollen, and the other, being a kettle, was probably protected from lacustrine deposition during the "late-glacial" phase.

INTRODUCTION

THE sequence of postglacial climatic changes in eastern United States, as recorded by pollen assemblages in lake and bog sediments, has been the subject of intensive study in recent years, and its broad outlines have become increasingly

clear. Its fundamental similarity to the much more detailed pollen stratigraphy of western Europe has been noted by several students, most recently by the author (Deevey, 1949). There is one great difference between North American and European pollen diagrams, however, which has been known for so long that most American authors have come to ignore it, evidently regarding it as a fact of nature. This is the absence, at the base of American sections, of a zone of sediment recording what European workers call "the late-glacial" (Firbas, 1934, 1939; Godwin, 1947). American diagrams begin in a "pre-boreal" cool phase marked by pollen of spruce and fir, and no undeniable indication of a tundra vegetation has come to light. Since the great majority of borings have been made in bogs that occupy kettles, it has often been suggested that deglaciation of eastern North America was followed immediately by forests of spruce and fir, which, at least locally, *i.e.* at the sites of the kettles, may have grown over masses of ice buried in outwash.

Although this conception of the early stages of retreat of the North American ice sheets gains plausibility from present-day conditions around certain Alaskan glaciers, such as the Malaspina, it rests almost entirely on negative evidence. There is some negative evidence against it: if the great outwash plains that commonly lie beyond the recessional moraines of the later Wisconsin substages in the middle West were covered by extensive forests during part of the time of their formation, one might expect far more fossil wood than has actually been found buried in outwash. But it is by no means certain, even in the kettles, that traces of tundra vegetation are missing. The fact is that most American pollen stratigraphers have not looked hard enough for it. They have largely confined their attention to the organic sediments of peat bogs, and when the pollen-poor clays and sands have been reached below the organic deposits they have generally stopped boring. It must be admitted that this attitude has been partly justified by experience, for the older, mineral sediments are often exceedingly sterile, and fail to yield pollen even to the most refined techniques of concentration. To push the postglacial pollen chronology back of the spruce-fir zone requires not merely perseverence, but geologic good fortune.

In reporting some success in this difficult task the author

can claim no credit for unusual persistence, for with the example of his European colleagues always before him, it has merely been routine practice to try to extract pollen from all sediments accessible with the peat borer. Good fortune was finally achieved on a brief reconnaissance of northern Aroostook County, Maine, conducted in the summer of 1949. The field trip to Maine was undertaken in part because a study of the data obtained by Potzger and Friesner (1948) suggested that the "rock flour" underlying the peat in certain bogs of coastal Maine contains unusually high proportions of grass and other non-arboreal pollen, indicative of deposition in a treeless region. It also seemed desirable, in establishing a far-flung geographic grid of samples for the calibration of the pollen chronology by means of radiocarbon analysis, to include northern Maine as the northernmost point that could be easily and quickly reached from New Haven.

Although borings were made at eight localities in Maine, in addition to several in Massachusetts, northern Connecticut, and eastern New York, the present paper reports on only six of these, four in northern Aroostook County and two in Kennebec County, Maine. The geology of coastal Maine is so complicated by the problematic relations of land and sea in late-glacial time, that it can not be adequately represented by two borings (in which the clay samples are unfortunately almost devoid of pollen).

It is a pleasure to acknowledge indispensable assistance, financially, from the Scientific Research Society of America and from the Connecticut Geological and Natural History Survey, and in the field, from my wife, Georgiana B. Deevey. Several lake-shore residents and owners of boats, too numerous to mention individually, provided most valuable cooperation.

METHODS

The author's preference for lakes instead of bogs as sites for pollen diagrams, a matter on which Faegri (1944) is in cordial agreement, has been reinforced by experience in Maine. The State is notably rich in bogs, many of them of vast extent and of great economic importance (Bastin and Davis, 1909; Trefethen and Bradford, 1944), but exceedingly few of them offer much promise of providing a complete postglacial stratigraphy. Most of them appear shallow and densely forested,

and their centers are almost inaccessible; to judge from the numerous sections given by Bastin and Davis, the majority represent recent paludification of upland soils, their origin perhaps dating from the deterioration of climate of the last two thousand years or so. Others, the great raised bogs of eastern Maine, for example, which may have a longer history as basins of deposition, have ceased depositing appreciable amounts of sediments at some time in the more or less distant past. Some sections published by Potzger and Friesner, and most of those from adjacent parts of eastern Canada published by Auer (1930), are obviously incomplete at the top as well as at the bottom. Moreover, even for the parts of the postglacial section that are actually represented in bogs, lacustrine gyttja is equal, if not superior, to peat on account of its larger proportion and better preservation of pollen. The formation of peat of various types is sensitive to minor fluctuations of climate, as the establishment of "recurrence surfaces" in European bogs makes clear (Granlund, 1932; see also recent summaries in Wenner, 1947, and von Post, 1946); at the present stage of North American investigations, however, a refined peat stratigraphy is a luxury that is more likely to confuse than to elucidate the postglacial chronology.

Five of the localities reported here are lakes, although four of them have boggy margins; all five were bored from boats and not from the bog mat. The sixth locality, Bishop Pond, is a more typical bog, and its pollen profile (fig. 5) indicates that it is incomplete at the top.

Davis peat borers of two sizes, the standard one of ¾-inch inside diameter and one of 1-inch inside diameter, were used throughout the work. The Davis borer is easier to use and to clean than the Hiller type, but is less suitable for exact stratigraphic work, particularly when it is desirable, as it would have been in Maine, to take samples 5 cm. or less apart. Attempts to improve the accuracy of the work with the Davis instrument took two forms, neither of which was wholly successful. First, since it is not practicable to take a continuous series of samples representing 25 cm. of sediment in the same hole, two holes were used alternately, with samples 50 cm. apart in each. Unfortunately, it can happen that the stratigraphy differs, even in two holes less than a meter apart. (The contemporaneity of successive samples at the "same level" in

adjacent holes has been critically discussed by Deevey and Potzger, 1951 *in press*). Second, in order to refine the stratigraphic work based on samples originally 25 cm. long (before compression), a series of intermediate samples was taken, as follows: after discarding the (possibly contaminated) lower 2 or 3 centimeters of a core, a cork borer was used to sample the next 2 or 3 centimeters. The peat sampler was then partially closed, extruding about half the estimated length of the core. This half, except for the small fraction obtained by the cork borer, was discarded, and the cork borer used in the same way to sample the upper half of the core. The original stratigraphic position of the samples is impossible to state precisely, but on the average the "number 2" samples should have come from about 12.5 cm. above the "number 1" samples. In plotting pollen diagrams, however, (figs. 2-7), the "number 2" bars have been drawn above and immediately adjacent to the "number 1's." The sampling interval of about 12.5 cm. gave a far more satisfactory picture than the one-foot interval that has been customary in work with the Davis borer, but it was not short enough in critical regions of the profiles.

In making pollen preparations the ordinary KOH method was used wherever possible, HCl being employed for calcareous sediments and HF for the silts and clays. The Erdtman acetolysis method gave unsatisfactory results in the few instances where it was tried; contrary to the previous experience of many pollen workers, including the author, the process was found to destroy certain pollen grains differentially.

In general, at least 100, almost invariably 150 pollen grains were counted at each level. No statistical significance is attached to differences between successive samples when the total number counted is so small. Problems of pollen statistics have been discussed at length elsewhere (Deevey and Potzger, 1951 *in press*), with the gloomy conclusion that almost all pollen counting as hitherto practiced is devoid of statistical significance. Fortunately pollen stratigraphy does not rest on a strictly statistical foundation.

The test of the stratigraphic validity of a change in pollen flora is not the precision of estimate of pollen frequencies at any one level, but whether the change occurs consistently in a whole group of sections from a particular region and can be firmly correlated with changes even farther afield that are

ecologically rather than mathematically analogous. This generally admitted fact implies that under certain circumstances it may be quixotic to count as many as 100 pollen grains, since all the information that can reasonably be expected, having regard to the effort required, can be extracted from smaller counts. In the older parts of the profiles reported here, where the pollen density is exceedingly low, counting has occasionally been terminated between 60 and 100 grains (or fewer in five cases, the minimum being 47), and in these counts only the proportion of non-arboreal to forest tree pollen is considered to have any reliability whatever.

REGIONAL GEOGRAPHY

Northern Aroostook County, the region of greatest interest in the present report, is a maturely dissected, drift-covered plateau with a general elevation of 500 to 800 feet, constructed for the most part of sedimentary rocks, including limestones, of Silurian, Devonian, and Mississippian ages. The principal river, the Aroostook, pursues a generally easterly course to join the St. John River a few miles east of the international boundary in New Brunswick. The St. John River forms the international boundary over part of its easterly reach, but its southward course to St. John on the Bay of Fundy lies wholly within New Brunswick (See sketch map, fig. 1). The country to the west of the valley of the Aroostook is higher and virtually inaccessible overland except from the Quebec side. A search of the literature suggests that northern Aroostook County has never been seriously studied by ecologists, but the author's trip to the region was too hurried to warrant an attempt at a general account.

With the improvement in communications and in living conditions during the present century the Aroostook country has been opened up rather rapidly. As the limestone rocks of the basin provide some of the best agricultural soils of New England, much of the land has been cleared of forests and cultivated intensively for potatoes, with the result that the landscape is a treeless downland similar to eastern Iowa. The resemblance vanishes abruptly in the neighborhood of local depressions, many of which are poorly drained, for here are found the spruce forests that may formerly have been much more extensive.

The role of the spruces in the natural vegetation of the region should not be overestimated from the widespread occurrence of black spruce (*Picea mariana*) in boggy situations. The climax dominant of the northern coniferous forest is not black, but white spruce (*P. canadensis*). Maps of vegetation types showing northern Maine as part of the northern coniferous forest (the "northern pine belt" of Sargent, 1884; the "St. Lawrence-Great Lake region" of Harshberger, 1911; the "northern mesophytic evergreen forest" of Shreve, 1917; the "spruce-fir" forest of Shantz and Zon, 1924; the "boreal forest" of Weaver and Clements, 1929) are in error. From the point of view of the climatic climax, the whole of New England belongs to the "hemlock-white pine-northern hardwood forest" of Nichols (1935). But this association-type itself is trans-

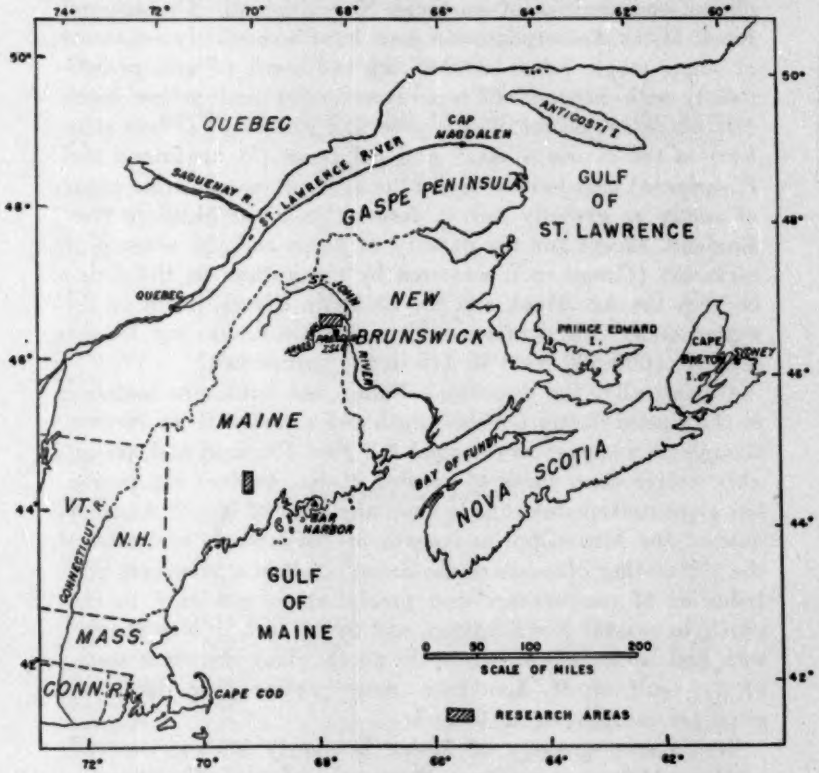

Fig. 1. Sketch map of Maine and adjacent parts of eastern Canada.

itional in many respects between the northern coniferous forest and the southern deciduous forest, as Nichols recognized, and northern Maine, like the part of Cape Breton Island that Nichols studied, is close to its northern boundary. This means that there is a confusing interdigitation of climax associations and a mixture of vegetation types that cannot be adequately represented on a small-scale map. At high altitudes, which are discontinuously present in Aroostook County and much more extensive in central Maine, there are great areas of northern coniferous forest; so, also, are spruce bogs abundant and extensive in central and southern Maine. It is therefore not surprising that most of the standard vegetation maps, which are aimed at the requirements of forestry or constructed from the data of forestry, give a misleading impression of the climax communities of northern New England. The original forest of the Aroostook basin must have been mainly composed of sugar maple (*Acer saccharum*) and beech (*Fagus grandifolia*), with hemlock (*Tsuga canadensis*) and yellow birch (*Betula lutea*) on the moister sites and white pine (*Pinus strobus*) in the clearings. Jack and red pines (*P. banksiana* and *P. resinosa*) may have occupied the flood plains and other areas of sandy or gravelly soil. A forest typical of southern New England, except for the paucity of beech and the absence of hickories (*Carya* sp.), was seen by the author on the divide between the Aroostook and the St. John Rivers, *north* of the region under consideration; this watershed lies at too low an altitude (600-800 feet) to fall in the spruce belt.

Climatically, the Aroostook Valley can hardly be matched in the United States for the length and severity of its winters, though its summers are normal for New England and noticeably hotter than those of coastal Maine. In fact the region has more continental climate than any part of North America east of the Mississippi and south of the latitude of Quebec; the moderating influence of the ocean is felt in a more even distribution of temperature and precipitation, not only to the south, in coastal New England, and to the east, in New Brunswick and Nova Scotia, but to the north, along the south shore of the Gulf of St. Lawrence. Some meteorologic data are given for comparison in table 1.

The glacial geology of Maine is poorly known, that of northern Maine especially so. Summaries of available informa-

tion, resulting from work that was hardly more than reconnaissance, are given by Stone (1899) and by Leavitt and Perkins (1935). The outstanding glacial features of the coastal district are the great northward-trending esker systems, which occur there on a grander scale than anywhere else in North America. In late-glacial time the coastal region was overlapped by the sea, and marine deposits (the "Leda clays") deeply cover certain lower parts of the state, but the relation between the formation of the eskers and the marine invasion is prob-

TABLE 1

Climatic data for Presque Isle, Aroostook County, Maine, with comparative figures for Quebec to the west, Cap Magdalen to the northeast, Sydney to the east, and Bar Harbor to the south. Sources: Monthly Record, Meteorological Observations in Canada and Newfoundland, and Climatological Data (U. S. Weather Bureau).

	Presque Isle, Maine	Quebec, Quebec	Cap Magdalen, Quebec	Sydney, N. S.	Bar Harbor, Maine
			Temperature, °F		
January	10.7	9.7	11.4	22.2	22.6
February	13.3	11.5	13.8	19.8	22.1
March	23.7	22.3	21.5	27.4	31.7
April	37.4	36.4	32.0	36.3	41.2
May	50.5	50.9	43.5	46.2	52.0
June	58.8	61.3	53.0	55.7	60.0
July	65.7	66.7	61.2	63.6	66.1
August	63.3	63.6	59.2	63.8	64.8
September	54.4	55.6	52.0	57.2	58.6
October	44.1	43.5	41.7	48.0	48.0
November	30.1	29.7	29.7	38.3	38.7
December	16.0	15.6	17.2	28.7	26.8
Mean	39.0	38.5	36.4	42.3	44.4
			Precipitation, inches		
January	2.26	3.75	2.47	5.16	4.75
February	1.83	3.14	2.55	4.45	3.85
March	2.22	3.22	2.77	4.45	4.80
April	2.61	2.40	1.77	4.03	3.75
May	2.87	3.16	2.58	3.44	3.35
June	3.70	3.94	2.89	2.84	3.27
July	3.72	4.07	3.12	3.27	3.36
August	3.10	3.92	2.81	3.75	3.25
September	3.39	4.01	2.33	3.46	3.97
October	3.36	3.47	3.09	4.70	4.38
November	2.52	3.55	2.76	5.17	4.55
December	2.38	3.43	2.72	5.45	4.38
Total	33.96	42.06	31.86	50.17	47.66

lematic, since some eskers overlie the clays while others are almost blanketed by them. Subsequent to the marine stage Maine underwent differential uplift toward the north, but the isobases have not been established with certainty. Leavitt and Perkins gave a map (1935, fig. 36) purporting to show the "elevation of marine features", with its highest isobase (450 feet) in south-central Maine, striking NE-SW on a line running south of Mt. Katahdin, but a study of the text gives no confidence that the features mapped are really marine. According to the authors, "deltas record best the marine levels in the regions where they occur" (p. 199), but some or all of the deltas may have been built in lakes and not in the ocean. The marine clays themselves have of course been dissected and partly removed since the uplift, but a map showing the maximum height now attained by deposits containing marine fossils would be more useful and less misleading than the one published by Leavitt and Perkins.

The esker zone ends somewhere in the wilderness of central Maine, and no eskers are present in northern Aroostook County. Little can be said of the glacial geology of this region except that the till is thick, as would be expected in a limestone country. It is reasonably certain, as discussed below, that the late-glacial marine invasion never reached so far inland.

Two lines of evidence suggest that ice advanced over Maine more than once: two sets of glacial striae of different direction have been reported, one set being superimposed on the other in some localities; there is also the fact that some eskers antedate a time of marine deposition, while others apparently postdate one (it is not clear that there was only one marine invasion). The evidence is too scanty to establish that there were two ice advances, let alone whether they should be referred to more than one glacial age or to two sub-ages of the Wisconsin glacial age.

NOTES ON LOCALITIES STUDIED

Plissey Pond, Washburn.—This is a small lake (elevation 620 feet) with a boggy margin, occupying an uncleared depression almost surrounded by potato fields. The outlet, Kennard Brook, reaches the Aroostook River after passing through other boggy areas. The bog mat is only partially

forested by black spruce and larch (*Larix laricina*); much of the mat vegetation is sedgy rather than ericaceous, and carries paper and gray birch (*Betula papyrifera* and *B. populifolia*) as well as alders (*Alnus* sp.) and red-osier dogwood (*Cornus stolonifera*). The lake is very shallow, carpeted by *Chara*, and has a few small, probably floating islands bearing cat-tails (*Typha latifolia*).

Some preliminary exploration with the peat borer indicated that the sediment is shallow, 3 to 5 meters, under most of the marginal mat, with a thin layer of high-grade shell marl intercalated between the peat and the underlying clay. A sounding in the center of the lake showed a total depth to hardpan of 8.4 meters, including a meter or so of water. The definitive boring was made just off the bog mat at the north end of the lake in a hole 10.8 meters deep and of very limited extent. Pure marl is lacking in this region, for, as is well known, the deeper, colder waters of stratified lakes can and usually do contain more dissolved carbon dioxide than the shallower waters, and marl is not so readily formed under such conditions (see the work of Groschopf (1936) on the Grosser Plöner See, for example). The lower layers of gyttja are grayish, however, and the upper clay is somewhat marly.

The existence of several stratigraphic markers of this sort added interest to the field work, but also helped to cast doubt on the validity of the geologic section obtained with the borer. The two borings synthesized in figure 2 were made as described above, the even half-meter samples being taken in one hole and the odd half-meter (one-quarter and three-quarter meter) samples in the other. Although the two holes were less than 50 cm. apart at the surface, the boundary of the marly clay came at mark 8.75 in one series and at mark 9.50 in the other. The depth to hardpan was precisely the same in both holes, and the pollen diagram (fig. 2) gives no reason to think that the stratigraphy is peculiar or confounded except in the vicinity, or conceivably everywhere below, about 9 meters. The two pairs of samples plotted at 9.40 and 9.65 meters are quite probably in reversed stratigraphic order (the curious fractions used here as elsewhere are explained by the length of the sampler head, 40 cm. closed and 65 cm. open). Unfortunately time did not permit an attempt to disentangle this confusion, which evidently arises from wedges of sediment.

After completion of the boring, three samples for radiocarbon analysis were taken half a canoe-length farther out in the lake at 3.65, 4.65, and 6.50 meters, by means of the gigantic Hiller sampler designed for the purpose (Deevey and Potzger, 1951 *in press*). A composite sample was also taken at 8.65 meters by the multiple-shot method. The total depth of deposit here was also 10.8 meters.

Caribou Lake, Washburn.—A considerably larger lake than Plissey Pond, Caribou Lake (elevation 548 feet) is otherwise

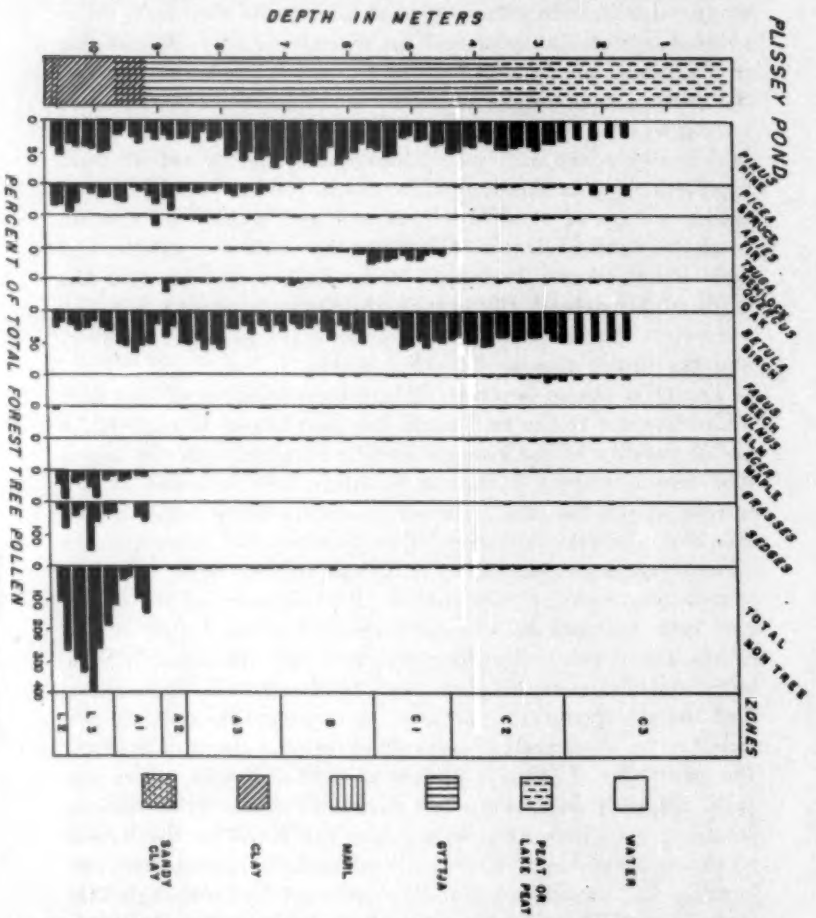

Fig. 2. Pollen diagram for Plissey Pond, Washburn, Aroostook County, Maine.

rather similar. The margin, including the outlet end, where a sluggish stream carries water to Caribou Stream, and thence to the Aroostook River, is surrounded by spruce bog. The

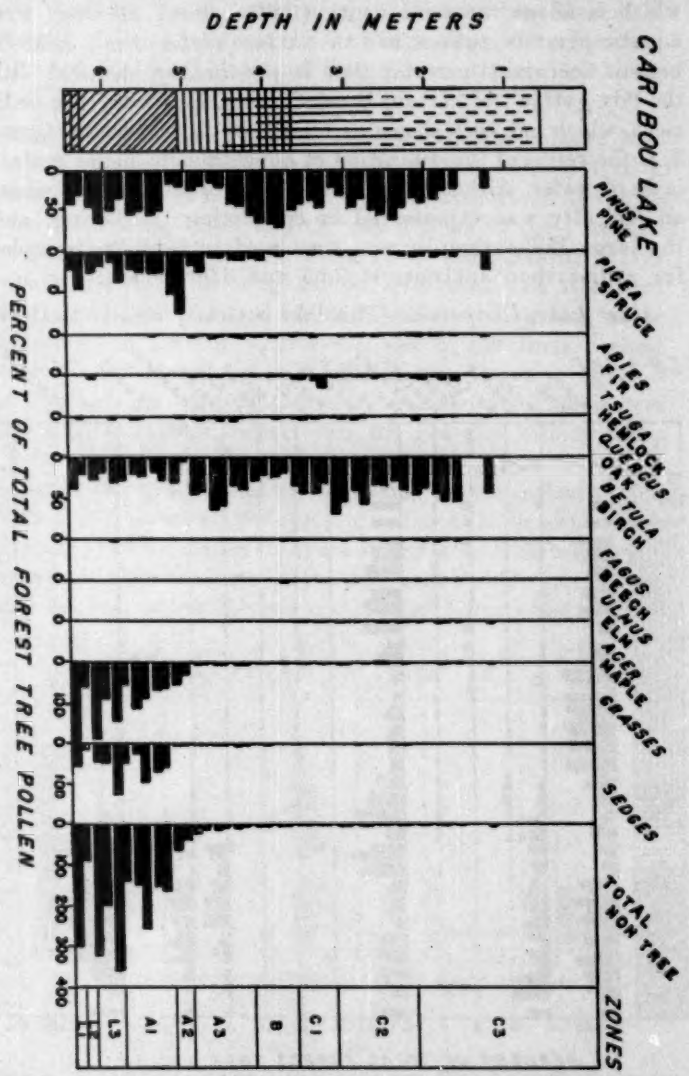

Fig. 3. Pollen diagram for Caribou Lake, Washburn, Aroostook County, Maine.

latter was not seen at close hand, for the boring was made in the deepest part of the basin that could be found. The total depth to hard bottom here was 6.45 meters, including the water, which is about the same depth (0.65 meters) all over. Few aquatic plants were seen, and the surface sediment is a reddish-brown, flocculant material that is presumably identical with the "dy-gyttja" of certain Swedish lakes. Evidently this sediment, which has been shown as lake peat in the section, figure 3, is the result of the deposition of allochthonous humic matter in hard water. Although the only boat available was a canoe, no difficulty was experienced in completing the boring, and the large Hiller sampler was then used to take two samples for radiocarbon analysis, at 2.65 and 3.90 meters.

Alder Lake, Chapman.—This lake is closely similar to Cari-

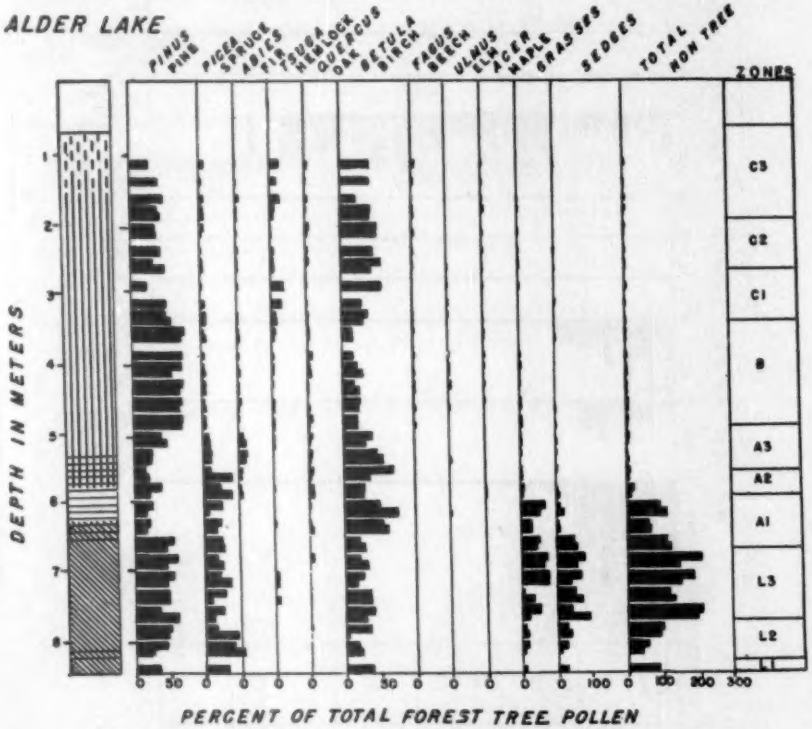

Fig. 4. Pollen diagram for Alder Lake, Chapman, Aroostook County, Maine.

bou Lake, but lies at a considerably higher altitude (663 feet), being tucked in a notch of Hedgehog Mountain in a way that suggested that it should be an ideal sediment trap. Drainage is to Alder Brook and thence to Presque Isle Stream, a tributary of the Aroostook River. The boring was made near the center in a total depth of 8.40 meters, the section being normal for the region (fig. 4).

Bishop Pond, Fort Fairfield.—Unlike the three lakes just described, Bishop Pond is little more than a wide part of a stream that wanders through a boggy valley bottom. It lies at an elevation of 660 feet, and the outlet flows to the Presquile River, which reaches the St. John River independently. This is one of the bogs investigated by Trefethen and Bradford (1944), and their sections indicate that the basin was never occupied by a lake of appreciable depth, for their deepest boring did not exceed 4 meters. The boring shown in figure 5 was made at the edge of the pond, and is only 3.80 meters long; a little farther downstream the gravelly subsoil comes to the surface. A handsome forest of black spruce and larch surrounds the pond on all sides, making access difficult.

The profile shows all the types of sediment to be expected in the region, but the pollen diagram suggests that little sediment has formed since the time of the pine zone; unfortunately the upper 65 cm., above the end of the peat borer when open at

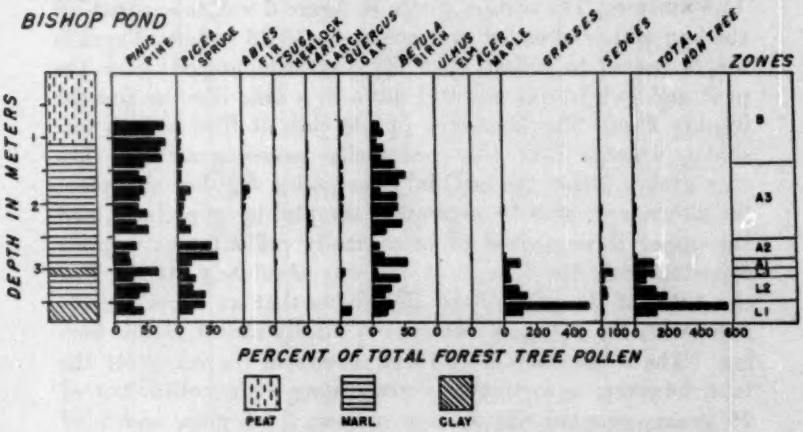

Fig. 5. Pollen diagram for Bishop Pond bog, Fort Fairfield, Aroostook County, Maine.

mark 0, could not be sampled without special pains, and they were not taken. The lower part of the section is remarkably informative, considering its small depth and the coarse sampling interval. Trefethen and Bradford reported shells occurring in the clay, and on this evidence they remarked that this "extends the limits of postglacial marine invasion into this area" (p. 9), but there can be little doubt that the shells occurred in the marl, either above or below the upper of two layers of clay, and that the shells were of fresh-water species. Shells of such species were abundant in the marly parts of the boring made by the writer, and there is no reason whatever to suppose that the clay is marine.

Muddy Pond, Oakland.—This small, bog-margined lake lies at 250 feet elevation in a minor depression near the lower (northern) end of the basin that holds Messalonskee Lake, in Kennebec County. Probably it was once an arm of the main lake, but at present the basins are separated by a sill less than 20 feet above lake level, and the spruce bog is confined to the Muddy Pond flank; Messalonskee Lake is presumably very much deeper than 15.40 meters, the maximum depth reached under Muddy Pond with the peat borer.

Muddy Pond is less than 4 meters deep, but a preliminary attempt to make a boring in the deepest part was given up on account of the impenetrability of the clay deposits below 15.40 meters. The section shown in figure 6 was taken just off the bog mat, and ended at hardpan in 10.35 meters. There is ample reason to believe that the clay encountered below the peat and gyttja was not laid down in a lake like the present Muddy Pond. The boundary of the clay at 8.40 meters was sharp, whereas lake clay ordinarily passes gradually into clay-gyttja. Below the boundary the pollen vanished abruptly; the 25 cm. core at 8.40 meters was sampled in four places, and the upper three proved to be normally polliniferous organic deposits, while the lowermost one was absolutely sterile. The character of the pollen flora also shows that an unconformity is present, for the spruce-fir zone is totally absent in this boring. (The single sample at 15.40 meters in the center of the lake, however, is a dark clay containing little pollen, but of 26 grains counted, 22 were of spruce, 2 of pine, and 2 of sedge.) The clay under the peat nearer the bog margin shows dark zones, not at the uppermost level, but lower down, about

9.0 to 9.5 meters. These zones contain little more pollen than the rest of the clay, too little to count in any case. The most convincing evidence that there is something abnormal about this clay is the occurrence of what appears to be the internal cast of a shell of *Mytilus edulis* at 9.15 meters.

More work is obviously needed, but it is reasonably evident that marine clay underlies the organic sediments of Muddy

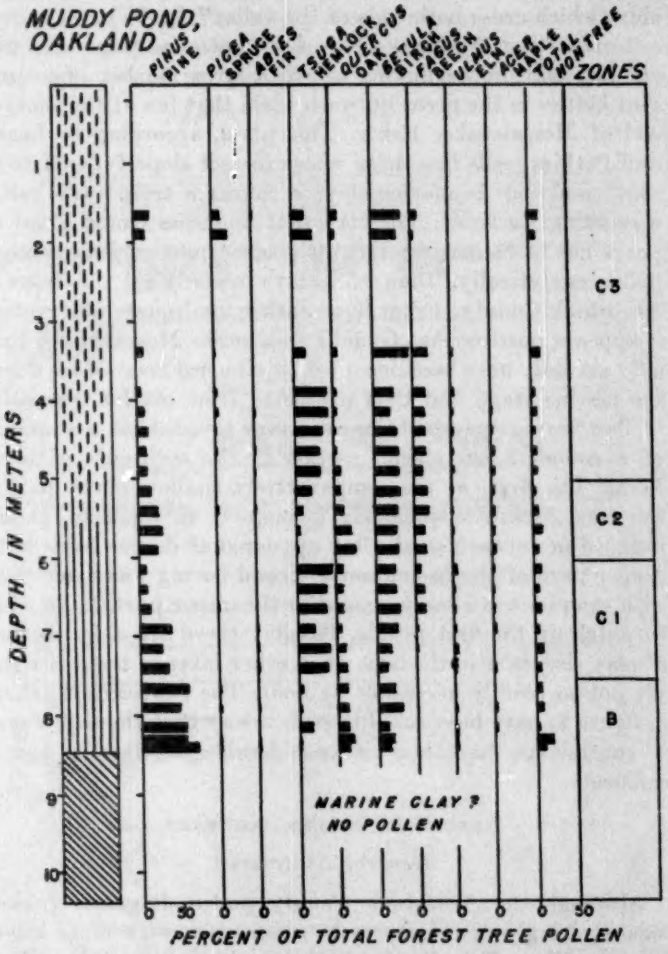

Fig. 6. Pollen diagram for Muddy Pond, Oakland, Kennebec County, Maine.

Pond. It is highly probable that it also underlies Messalonskee Lake itself. According to Leavitt and Perkins (1935), however, the lake basin is of unusual interest in lacking marine clay, and "the northern part of Messalonskee Lake at Oakland appears to have been a giant kettle . . ., in which a mass of ice may have lingered through the marine stage, preventing the entrance of the sea and the filling of the basin by marine clays which cross both ends of the valley" (p. 51).

Gould Pond, Sydney.—This is a typical seepage lake without bog margin, occupying one of a large number of magnificent kettles in the great outwash plain that lies at the southern end of Messalonskee Esker. This plain, according to Leavitt and Perkins, ends in a delta whose foreset slope falls off to the south and ends in marine clay; it marks a temporary halt of a receding ice front. The clay that underlies Gould Pond appears not to be marine, and the deepest part of it is younger, pollen-analytically, than the clays underlying the lakes of Aroostook County. From these rather inadequate observations it appears possible that Gould Pond, unlike Messalonskee Lake, may actually have been occupied by a buried mass of ice during the marine stage and thus protected from marine deposition.

Two borings proved to be necessary to establish a semblance of a complete postglacial section in the sediments of Gould Pond. The first, in the comparatively shallow north part of the lake, looked suspiciously incomplete in the field, though it ended in outwash sand. Clay appeared at deeper levels in the deeper part of the basin, and a second boring was made there, with samples less closely spaced in the upper part, in an effort to patch up the first profile. Possibly there are older deposits of clay elsewhere in the lake, or in other lakes of the series that are not so readily accessible by boat. The two sections, shown in figure 7, have been fused in such a way that the depth scale is continuous, but there is considerable overlap in age of sediments.

REGIONAL POLLEN SEQUENCE

General Statement

Although the Aroostook County pollen diagrams present some strikingly new features in comparison with those known from southern New England, their zonation is rather clear, and the fact that they are largely dominated by pine and birch

pollen and are nearly or completely devoid of oak, beech, and hickory does not hinder comparisons either locally or generally. The outstanding characteristic of the four profiles (figs. 2-5) is the occurrence near the bottom in sediments composed of silt, clay, or marl, of enormous quantities of grass and sedge pollen, the total non-arboreal component representing from 100 to nearly 600 per cent of the forest tree pollen. This preponderance of herbaceous pollen (with shrubs, such as alder and willow, contributing a minor fraction) can only mean that the vegetation of the period was a tundra, and that the tree

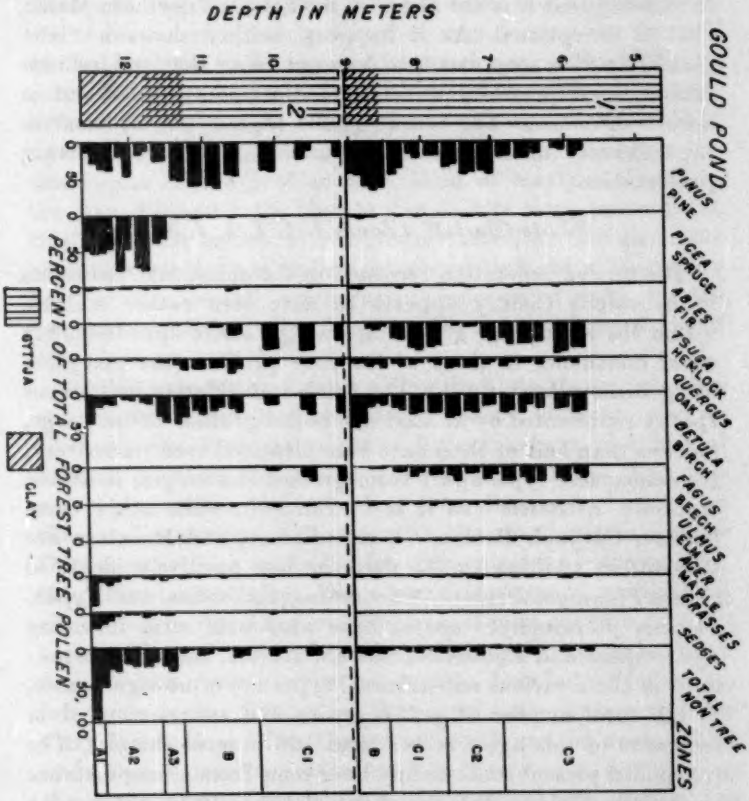

Fig. 7. Pollen diagram for two borings in Gould Pond, Sidney, Kennebec County, Maine. The two diagrams are joined at a point of equivalent depth from the lake surface, but the upper part of boring 2 overlaps boring 1 in respect to age.

pollen (composed of pine, spruce, and birch in about equal proportions, with an occasional grain of oak, beech, or hemlock) was blown from a great distance. In all essential respects this older zone corresponds to the "late-glacial" of northern Europe, and these are the first North American pollen diagrams to show a complete sequence from tundra to postglacial forest.

The two localities in Kennebec County, about 175 miles SSW of the Aroostook County group, yield much more "orthodox" New England pollen profiles, and are of interest chiefly in showing that it is not Maine as a whole, but northern Maine, that is exceptional. As it happens, neither shows a "late-glacial" pollen zone, but this does not mean that tundra conditions never prevailed in southern Maine, as pointed out in a later discussion. The two diagrams (figs. 6 and 7) must be kept sharply distinct from the first four in the following presentation.

"*Late-Glacial*" (*Zones L 1, L 2, L 3*)

The tundra vegetation recorded in the oldest lake sediments in Aroostook County appears to have been rather uniform within the region, for grasses and sedges share approximately equal dominance in three of the four profiles (the exception being Bishop Pond, fig. 5). The number of different herbaceous species represented by at least one pollen grain is rather large, but less than half of them have been identified even tentatively; the commonest type, apart from grasses and sedges, is almost certainly *Artemisia* (as it is in Europe), while other Compositae, Caryophyllaceae, Chenopodiaceae, and Rosaceae are present, in addition to the more or less positively identified genera *Plantago*, *Drosera*, *Scleranthus*, *Epilobium*, and *Typha*. Various pteridophyte spores have also been seen, including *Lycopodium* and *Equisetum*, but not *Isoetes*. Relative proportions of these various non-arboreal types are of no significance, as the total number of pollen grains and spores counted in sediments of this age was less than 100 in most samples. The tree pollen present must mainly have come from a long distance away from the localities, as shown not merely by the similar proportions of the three dominants (pine, spruce, and birch), but by the almost invariable occurrence of one obviously stray grain (usually of oak, sometimes of hemlock, beech or elm)

in each count. The birch pollen, or some of it, may have been derived from thin birch woodland in the near vicinity, but it is impossible to be certain about this.

Sequences within the zone of tundra vegetation, though not established beyond doubt, owing to the coarse sampling interval, are sufficiently convincing to warrant the division into three zones, and this is the most astonishing feature of the Aroostook County diagrams, after the demonstration of the existence of the tundra itself. In three of the four sections there is a marked fall in the total non-arboreal component, usually to slightly less than 100 per cent, accompanied by a rise of birch and spruce pollen that may or may not be real. At this level the pollen density increases noticeably, although quantitative figures are not available, and the pollen frequency per unit area of smear is regarded as almost entirely without significance. More striking is the appearance, somewhere in this region of the profiles, of a band of marly sediment in the clay. Evidently the climate was a little more favorable at this time than before or immediately after, as though an ice advance somewhere in the neighborhood brought a temporary halt to the general amelioration represented both by the composition of the pollen flora and the nature of the sediment deposited.

Stratigraphic relationships within the "late-glacial," as they are inferred from this admittedly scanty evidence, are remarkably like those of northern Europe, where, in a belt of country distal to the Fennoscandian moraines and their presumed equivalents and extending from Russia to Ireland, an older and a younger zone of tundra climate (lower and upper *Dryas* zones) are separated by sediments of a warmer time, the Allerød oscillation. Many more analyses in vertical sequence will be necessary to convince a skeptic that the "Aroostook oscillation" is a reality. Even if it is real it must be shown to have had a much wider geographic distribution before its interpretation as sub-age of Wisconsin time (presumably the Cary-Mankato or Two Creeks interval) can be accepted as more than a remote possibility. For the present, however, on the grounds of its consistent occurrence in three profiles, the author has no qualms about recognizing it as a stratigraphic horizon, referring to it as *L 2*.

The Aroostook oscillation is most clearly shown at Bishop

Pond (fig. 5), where the band of marl is thickest, so that three analyses fall within it. At Plissey Pond (fig. 2), the section appears to begin in *L 2*, and *L 1* is missing. There is a possibility that the two samples at and just above 9.65 meters belong to *L 2*, but this is thought to be improbable because of the suggestion of confused stratigraphy, recounted in an earlier section.

The use of the expression "late-glacial" for the tundra zones is open to some objection, since it implies an arbitrary and logically erroneous usage for "postglacial." All pollen diagrams in formerly glaciated districts are postglacial, of course, but as the postglacial chronology gains refinement there is need to distinguish the time "when the fauna and flora were influenced by the presence of nearby ice from a time when they were not" (Deevey, 1949, p. 1325), geographically relative though these times may have been. From the point of view of pollen analysis the most convenient boundary between "late-glacial" and "postglacial" is the time marking the invasion of tundra by forest. This boundary is here considered to lie at the final and permanent fall of the non-arboreal pollen to values below 100 per cent. More than that is not implied by the term "late-glacial."

The pollen zone hitherto thought to be the oldest in North American diagrams is the spruce-fir zone, designated "*A*" by the author (Deevey, 1939, 1943) and "I" by Sears (1942). The classification must now be revised, and it seems that less confusion will arise if alphabetical order is violated and the "late-glacial" zones given the general designation "*L.*" *L 1* and *L 3* are cold zones, and are separated by the slightly warmer but probably still treeless Aroostook oscillation, *L 2*.

First Postglacial Forest (*Zones A 1, A 2, A 3*)

The relative proportions of the forest tree pollen grains during the "late-glacial" should probably be disregarded, partly because all of these grains are considered to have been blown from a distance, and partly because the total number of grains counted was too low for reliability in most cases. The first sure indication of the arrival of forests in Maine is the fall of the non-arboreal component to values around 100 per cent. In four of the five diagrams recording this advance, including Gould Pond in central Maine but not including Caribou Lake in Aroostook County, birch is the first "arboreal"

type to take part in the rise. This is what would be expected during the advance of a forest onto a tundra, although the application of the term "forest" is open to debate; the forest was doubtless of the "little stick" variety.

The main rise of spruce pollen (leaving aside the rise during *L 2*, which is probably fictitious) follows the rise of birch in all profiles, and comes at the expense of birch. The non-arboreal component falls to "normal" values of around 10 per cent, the grasses and sedges disappearing almost completely and leaving the field to the usual non-tree types of local provenance, such as alders, willows, ericaceous shrubs, and pteridophytes. There can be little doubt that spruce forests were actually extensive at this time, and that Maine was part of the taiga.

The next feature of interest is a rise of fir, conspicuous in most borings despite the low percentages involved. Spruce remains high, and birch rises once more. The alder maximum (not shown in the diagrams) falls here in all of the Aroostook County sites. It is difficult to know how to interpret these events. The birch may have been a more warmth-loving species than the earlier pioneers, and the alder maximum may be the purely local result of shoaling of the lakes and the formation of swampy margins. These perfectly reasonable hypotheses imply steady climatic amelioration and advance of forests throughout the time of the spruce zone. On the other hand, fir is more likely to occupy outwash in recently deglaciated districts than is spruce, and birch and alder thickets may possibly have replaced spruce forests as a result of a slight deterioration of climate, since they are outposts on the tundra today. The question must be left open, and it may never be answered until the species of birch and alder can be identified with certainty.

The early forest time, "*A*," then, is divisible into three well-marked zones, *A 1*, birch woodland, *A 2*, spruce forest, and *A 3*, birch-fir-alder pollen maxima of uncertain climatic significance. No pollen diagrams hitherto published for North America show so clear or so complex a sequence, and the Maine zones may prove to be of only local validity. Regional correlations are discussed further below.

Pine Zone (B)

Pine pollen is generally high throughout the Maine borings, and on that account one might anticipate some difficulty in

picking out a zone characterized by high pine. That this is not the case is one of the most remarkable facts about a zone that is notably easy to pick out everywhere in eastern North America. Between the decline of spruce pollen to negligible quantities and the rise of members of the deciduous forest complex is a layer of sediment having consistently and extraordinarily high pine percentages. Its ecologic interpretation is something of a puzzle, as the author has emphasized elsewhere (Deevey, 1949). Because pine pollen is produced in abundance and is exceptionally light, pollen workers have grown accustomed to discounting pine values of 50 per cent or so as due to extreme over-representation, but figures of about 80 per cent (occasionally as high as 95 per cent) are the rule in the pine zone, and must imply the presence of a great many pine trees in the vicinity. It is commonplace to regard this period as one of warm, dry, continental climate, corresponding to the Boreal phase of western Europe, but in North America, in contrast to Europe, the pines seem to have replaced a taiga community, and this is difficult for an ecologist to understand. It is possible that the pines were dominant by default, so to speak, in that they lived on poor soils—outwash plains, kames, deltas, and the like, while deciduous forests had still not succeeded in colonizing the potentially better sites, and the climate was too warm for spruce forests, at least in the summer. The long time during which the pines seemingly held sway makes this a rather unsatisfactory explanation.

At all events, the pine zone (*B*) exists in the Maine diagrams as it does elsewhere. There is little evidence of differentiation within this zone; in parts of the middle West, notably in Minnesota, there is more than a suggestion that elm pollen reached a maximum early in the period, and this may be more generally true than is commonly realized, but it will be necessary to count more than 150 pollen grains to prove it in regions, such as Maine, where elm pollen does not exceed 3 per cent. Subdivision of the pine zone on the basis of the hazel pollen curve is practicable in parts of Europe, but not in North America. A useful feature of the Maine diagrams, though one that is probably of only local importance, is that the pine period terminates at a level of minimum birch pollen, but whereas pine undergoes no significant change during the next phase (*C 1*), birch rises again rather suddenly.

Deciduous Forest Zones (C 1, C 2, C 3)

The threefold division of the deciduous forest phase is maintained with admirable clarity in the Maine diagrams, despite the fact that the region is outside the ranges of hickory and chestnut, types that are highly characteristic farther south. The most distinctive picture, somewhat paradoxically, is given by the curve for hemlock, which is not a deciduous species, though it belongs to the deciduous forest community. In central Maine hemlock is the dominant type both in *C 1* and in *C 3*, and this is true elsewhere in New England north of the Connecticut and Massachusetts coast, where hemlock is subordinate to oak. In the form and strength of the hemlock curve the Kennebec County diagrams closely resemble those published from New Hampshire by Krauss and Kent (1944). In Aroostook County, however, though hemlock pollen shows the same characteristic oscillation, it is much less abundant than pollen of birch and pine. While proof is lacking, it is almost certain that the birch species involved here is mainly *Betula lutea*. The middle period of hemlock minimum is characterized by the oak maximum, as usual, but hickory pollen is absent, and there is a rise of pine, presumably equivalent climatically to one of hickory. The abruptness of the hemlock decline at this level is noteworthy. The final period, *C 3*, so far as it is recorded by incomplete sampling, saw a return of hemlock, birch, and spruce, and a decline of oak and pine.

The behavior of the beech pollen curve attracts special attention, because of the author's hypothesis (Deevey, 1949) that there were three waves of migration of beech in eastern North America, probably without climatic significance. The oldest is supposed to be recorded in New Jersey, while southern New England and Ohio witnessed only the second and third. On this view the Kennebec County localities are normal for New England in showing two rises, across the boundaries, *C 1-C 2* and *C 2-C 3*, while only the last is at all prominent in northern Maine. This is what would be expected if the migration of beech was relatively slow, with its rate governed more by distance from glacial refuges than by climatic controls. It is also another faithful reflection of events in northern Europe.

DISCUSSION

The strictly postglacial parts of the Maine pollen diagrams, beginning with the time of the spruce maximum, though peculiar

in some respects, offer no difficulty for correlation with the standard sequence of events in eastern North America. Attention must therefore be centered on the older zones, and an attempt made to decide the likelihood that they are uniquely characteristic of northern Maine. Certainly the climate and physiography of the region are peculiar enough to warrant the suspicion that this most continental part of the maritime peninsula of eastern Canada and United States must be in a class by itself. Moreover, the pollen diagrams from places in closest geographic proximity, those that Auer (1930) obtained in the Maritime Provinces, are as different as can well be imagined from those of the present report.

Auer's diagrams can be dismissed at once, because it is now clear that most of them are incomplete at the top. This is the result of making borings in bogs, particularly in raised bogs. They are also incomplete at the bottom, since the mineral sediments underlying the organic materials were not analyzed for pollen. So far as the wide sampling interval permits of a judgment, the published profiles agree well with the middle parts of the Maine diagrams, particularly with those from central Maine, since most of them are dominated by pine and birch, and many of them show the fall of spruce and the rise of pine, followed by the rise of hemlock, typical of Zones *A*, *B*, and *C 1*. The same features are shown by most of the diagrams from coastal Maine published by Potzger and Friesner (1948), but only one of these (Mullins Pond) can be accepted as essentially complete.

Potzger and Friesner made an effort to extract pollen from the clay underlying their bogs, but met with little success. This clay is presumably of marine origin, and so far it has proved sterile in the author's hands as well. Lake clays are not always so barren, however, and this is true in other localities beside the marl lakes of Aroostook County, which admittedly are exceptionally favorable. The oldest sediments in Linsley Pond and Upper Linsley Pond, Connecticut, for example, are not devoid of pollen; those of Upper Linsley, at least, also show the high non-arboreal pollen percentages characteristic of the "late-glacial," as a re-investigation has shown. The new diagram, which was made in connection with sampling for radiocarbon dating, has been published by Deevey and Potzger (1951 *in press*). The absence of the "*L*" zones in the earlier analyses

(Deevey, 1939, 1943) cannot be satisfactorily explained; it may have been merely due to failure to record all the non-arboreal pollen, but as some of the data sheets from the 1939 investigation show high values for grass or sedge, while none of those for the 1943 series do so, it is probable that the coarse sampling interval employed was the cause of the oversight. Be that as it may, northern Maine is evidently not unique in showing a zone of tundra climate. And if southern Connecticut once had such a climate, it is quite probable that southern Maine did also.

We are accordingly obliged to scrutinize the "*A*" zone of other North American pollen diagrams for evidence of "late-glacial" conditions. One feature in particular seems to require a completely different interpretation. In many diagrams spruce pollen rises before it falls. Where a fir maximum precedes the spruce maximum it is reasonable to suppose that ecologic succession was involved, but this is not the usual sequence. More often the fir maximum accompanies or follows the spruce maximum, and the older pollen flora is mainly of pine. Such a spruce rise has hitherto been thought to signify climatic deterioration, perhaps a re-advance of ice in the vicinity (Deevey, 1939, 1949). It now appears more probable that the spruce rise records the actual invasion of spruce into the region, the older spruce (and pine) pollen having been wind-borne from a distance. If only forest tree pollen grains are counted or recorded in pollen diagrams, the full implications of their proportions can easily be overlooked.

It follows that some or all of what has sometimes been called Zone *A 1* very probably belongs to the late-glacial "*L*" zones. Zone *A 2*, which in Connecticut has been considered to begin with the spruce maximum, may be correlated with Zone *A 2* in Maine, and the birch maximum of *A 1* as now recognized may simply have been missed before. Zone *A 3* of Maine is also discernible in southern New England.

It is unfortunately true that if some appreciable fraction of the pollen from the spruce-fir zone was blown for a long distance over a treeless belt, most of the basis for the reconstruction of glacial refuges and routes of postglacial dispersal of forest trees, as worked out particularly by Sears (1941), must fall to the ground. Sears' maps for postglacial migration of oak, hemlock, beech, and basswood were based on their rela-

tive order of appearance in a large number of pollen diagrams, but the order of appearance could easily be irrelevant at any given site if the pollen in question was not of local derivation. The fact that maverick grains, especially of oak, are comparatively abundant in the "*L*" zones of Maine points to this disappointing conclusion.

The sequence of pollen zones is summarized in table 2, which is designed to call attention to the remarkably close correlation with western Europe. The Irish stratigraphy (Jessen, 1949) has been chosen because Ireland is nearest to America

TABLE 2

Tentative correlation of pollen sequences in northern Maine with those from Newfoundland-Labrador (Wenner, 1947) and Ireland (Jessen, 1949). Horizontal lines do not imply contemporaneity of zones. NAP = non-arboreal pollen.

	Maine	Newfoundland-Labrador		Ireland
Zones	Pollen flora	Pollen flora	Zones	Pollen Flora
C3	Hemlock, spruce return; beech maximum	Return of tundra pollen	VIII	Alder-birch-oak
C2	Oak maximum, pine rises; hemlock, beech at minimum	Conifer maximum	VIIb	Alder-oak
C1	Hemlock maximum; birch rises, oak and beech present		VIIa	Alder-oak-pine
B	Pine maximum; birch falls		VI	Hazel-pine
A3	Fir and birch rise, spruce still high; alder maximum	Subarctic alder forest	V	Hazel-birch
A2	Spruce maximum; birch falls			
A1	Birch rises, NAP falls; end of tundra		IV	Birch
L3	NAP higher		III	Younger *Salix herbacea*
L2	NAP lower; spruce and birch rise		II	Birch (Allerød)
L1	NAP high; long-distance transport of pine, spruce, and birch		I	Older *Salix herbacea*

geographically, and the zonation of the Irish pollen diagrams has deliberately been brought into conformity with standard systems from elsewhere in the British Isles and from Denmark. Actually, Ireland has so maritime a climate that Jessen had some difficulty in distinguishing between zones that are much clearer in other parts of Europe. The similarity in details of pollen flora between Maine and Europe would appear much closer if Sweden had been chosen rather than Ireland. At present the details are considered to be less important than the fact of the correlation.

It should be emphasized that the transatlantic connection between zones by means of horizontal lines in table 2 implies no more than stratigraphic equivalence. Absolute contemporaneity should never be read into tables such as this, in view of the fact that similar tables are constructed for places situated on north-south lines, where we have every reason to doubt that stratigraphic equivalence means contemporaneity. Late-glacial and postglacial synchronism between eastern North America and western Europe will be discussed in another paper, when radiocarbon dates are reported.

Data from Newfoundland-Labrador are also incorporated in table 2. It is not easy to interpret the diagrams given by Wenner (1947), in part because he has used various unorthodox methods of computing pollen percentages, and has lumped all winged-grained conifer species together without tabulating their numbers. His highly interesting results have been inserted in the table in order to express a mild disagreement with the correlation set out on page 163 of his work. According to that interpretation, all of the sections, at least all those from the forested part of the region, date from Atlantic time or later, and the maximum of conifer pollen is referred to the xerothermic interval. The famous diagram published for southern Labrador by Bowman (1931) has been brought into line with its hemlock maximum falling in the xerothermic interval also (hemlock does not grow today within hundreds of miles of Bowman's site). It appears that Wenner was unduly influenced by his belief that all postglacial events in Labrador were compressed into a time-span very much shorter than postglacial time farther south. This is a reasonable belief, but it should be kept out of correlation tables until an absolute chronology is available. In the pollen-analytic sense it is more probable

that Wenner's conifer maximum and Bowman's hemlock maximum belong to *B* or *C 1*, not to *C 2*, and that the first postglacial forest zone is equivalent to some or all of *A*. New investigations in Quebec and southern Labrador are badly needed to clarify the correlation, particularly since there is reason to suspect that Bowman's section, which was made in a bog, is incomplete above and below.

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Osborn Zoological Laboratory
Yale University
New Haven, Connecticut

[American Journal of Science, Vol. 249, March, 1951, Pp. 208-214]

ALLANITE FROM WILMOT PASS, FIORDLAND, NEW ZEALAND

C. OSBORNE HUTTON

ABSTRACT. The occurrence of relatively large crystals of thorian allanite in microcline pegmatites in Fiordland, New Zealand, is described, and following careful separation from matrix and inclusions, the mineral has been analysed completely. Relevant physical data are as follows: $\alpha = 1.763$, $\beta = 1.768$, $\gamma = 1.788$; $2V = 57°$ (+); dispersion with $\rho > \nu$ is distinct; $D_{22}° = 3.99$. The mineral appears to be quite devoid of any metamictization and less than 0.01 per cent of lead has been determined spectrographically; the probable significance of the very low lead-ratio is discussed.

NOMENCLATURE

THE terms allanite and orthite have been used from time to time to denote cerium-bearing epidote group minerals, in which yttrium may also be present, with apparently little or no regard to earlier specification. The term allanite was originally intended to denote those smaller, unaltered crystals that were tabular parallel to the orthopinacoid, whereas orthite was reserved for large crystals of prismatic habit whose analyses showed a considerable degree of hydration and alteration. This nomenclature has been adopted by Lacroix (1922, p. 451) and others, but many workers have subsequently applied these terms in various ways, a few instances of which are as follows: Lokka (1935) has employed the term orthite to denote both the normal as well as the altered mineral; Mountain (1931), Simpson (1931), and Marble (1940) have designated the metamict, and therefore the altered varieties, as allanite; and Geijer (1927) has specifically used orthite to describe tabular crystals, the refractive indices of which appear to suggest little if any alteration and yet he has also described a cerium epidote of fibrous or prismatic habit as orthite. It would seem appropriate, therefore, to abandon the term orthite since in any event allanite has priority, and to use this latter name to signify cerium-bearing members of the epidote group, without regard to crystal habit, or degree of metamictization.

OCCURRENCE

The cerium-bearing epidote mineral, allanite, is a minor constituent of microcline pegmatites two miles northwest of Wilmot Pass, between Lake Manapouri and Deep Cove, Doubtful

Sound, Fiordland, New Zealand. The mineral has a characteristic habit and occurs in stout crystals, tabular parallel to the orthopinacoid, and they measure up to 12 mm. along the greatest diameter. Allanite, which is associated in the pegmatite with muscovite, rare zircon and cassiterite, is quite unaltered and is devoid of the rusty-colored alteration products that are often associated with this mineral. In addition there is a complete absence of any arrangement of anastomozing cracks radiating outwards from the allanite into the surrounding quartz and microcline as has so often been reported in other instances (Walker and Parsons, 1923; Richmond, 1937, p. 293).

Most of the crystals are minutely sieved with inclusions of quartz and feldspar and one in particular exhibited a narrow but sharply defined peripheral zone of moderately ferriferous but colorless epidote. This is not, however, an unusual feature of allanite and it has been recorded by Turner (1937, p. 231 *et seq.*) for allanite from rocks in this same general area, and by other authors (Lacroix, 1889, pp. 138-139; Hobbs, 1889, pp. 225-227; Lundegardh, 1947; Baker, 1937, pp. 49-50), although the "chevron-like" type of zoning described and illustrated by Lacroix and Baker was not found.

CHEMICAL PROPERTIES

In preparing material for analysis, fine-grinding to −230 mesh (U.S.S. screens) was found to be necessary in order to secure monomineralic particles completely freed from inclusions and zonal epidote. Following this treatment the powder was centrifuged in Clerici solution to secure the pure fraction for analysis. The analysis listed under A in table 1 is clearly that of an unaltered allanite with a normal percentage of water and ferric iron. Three analyses of allanite of similar composition are also listed in this table for comparative purposes although in a search through the literature available to the writer more comparable analyses were not found.

Careful dehydration of the allanite was carried out and it was found that little water was given off until a temperature of 250°C. had been reached, but complete dehydration appeared to be attained at 1040°C. This condition contrasts somewhat with the behavior of normal epidotes where a considerably higher temperature than 1040°C. is required to ensure the complete release of the hydroxyl (Smethurst, 1935). However, the

water content is comparable to that generally found in unaltered allanite (Lokka, 1935, p. 13, table 3) and the evidence of negligible loss of water at low temperatures is very distinct from the behavior of metamict allanites (Lokka, 1935, p. 19, diagram 1, curves Or DI, Or DII, Or B, and Or E) under similar circumstances.

The analysis has been recalculated (table 2) on the basis of 13(O, OH, F) atoms to the unit cell to conform to the formula evolved by Machatschki (1930) for other allanites, *viz.* $X_2 Y_3 Z_3 (O,OH,F)_{13}$, where

X = Ca, Ce, and other rare earths, La, Mn, K, Na.

Y = Al, Fe″′, Fe″, Mg, Ti

z = Si, and Al in part [presumably also Be in part, *vide* Quensel, 1945].

In this table it will be noted that only a negligible quantity of aluminum appears to occur in four co-ordination and this condition seems to be general in allanites (Lokka, 1935, pp. 11-12), and in members of the epidote group generally. Further, the purity of the sample analysed and its unaltered con-

TABLE 1

Analyses of Allanites

	A	B	C	D
SiO_2	32.20	30.42	33.73	32.97
Al_2O_3	17.18	17.00	16.09	16.10
Fe_2O_3	3.79	5.45	10.68	4.65
FeO	10.38	11.96	3.87	9.52
TiO_2	0.74	....	0.80	....
MgO	0.69	....	0.18	0.16
CaO	11.95	13.38	16.18	12.40
SrO	nt. fd.	....	....	....
MnO	0.26	0.80	0.06	0.90
Na_2O	trace	....	....	....
K_2O	0.02	....	....	0.17
ThO_2	1.05	2.37	....	0.33
Ce_2O_3	9.06	8.09	8.59	9.66
La_2O_3	9.24	8.31	6.96(Di_2O_3)	10.65(Di_2O_3)
Y_2O_3	0.72	1.42	1.10	....
H_2O+	1.89	0.58	1.69	1.96
H_2O-	0.29	0.15		
F	trace	....	....	....
	99.46	99.93	99.93	99.47

A. Wilmot Pass, Flordland, New Zealand. Analyst: F. T. Seelye; water and fluorine determinations by C. Osborne Hutton.

B. Madagascar (Carrobi, 1926).

C. Michalkowo (Kostov, 1940).

D. Greenland (Dana, 1892, pp. 524, analysis no. 22).

dition appears to be verified because analyses of metamict allanites often show excess of silicon over that required structurally. Similarly the negligible quantity of alkalies is also indicative of an unaltered condition since appreciable quantities of both soda and potash are often present in metamict varieties.

TABLE 2

Recalculation of Analysis of Wilmot Pass Allanite

	wt. per cent	no. of metal atoms	(O, OH, F)		
SiO_2	32.20	1.072	2.966		3.00
Al_2O_3	17.18	.504	1.871	0.014	
				1.857	
Fe_2O_3	3.79	.072	.267		3.06
FeO	10.38	.143	.796		
TiO_2	0.74	.018	.050		
MgO	0.69	.017	.095		
CaO	11.95	.214	1.192		1.89
MnO	0.26	.003	.016		
ThO_2	1.05	.008	.022		
Ce_2O_3	9.06	.081	.301		
La_2O_3	9.24	.087	.323		
Y_2O_3	0.72	.009	.034		
H_2O	1.89	.105	1.169		1.17

Formula:—$(Ca, Mn, Th, Ce, La, Y)_{1.89}\ (Al, Fe''', Fe'', Ti, Mg)_{3.06}\ \left[(Si, Al)\ O_4\right]_3\ (OH)_{1.17}$

A spectrographic analysis of the Wilmot Pass allanite showed that lead did not exceed 0.01 per cent and in addition the only notable trace elements were scandium and chromium.

The reaction of the finely powdered mineral to acids is interesting; the mineral is insoluble in concentrated hydrochloric or nitric acids. Fuming perchloric acid, however, completely dissolved the very finely powdered mineral although this reaction was sluggish. This is in marked contrast to the behavior of metamict allanites.

PHYSICAL PROPERTIES

The following properties were determined for Wilmot Pass allanite:

$\alpha = 1.763 \pm 0.003.$
$\beta = 1.768$
$\gamma = 1.788$
$\gamma - \alpha = 0.025$
X = pale brown.
Y = greenish brown.
Z = deep warm brown.
$Z \geqslant Y > X$

Dispersion: $\rho > \nu$, distinct.

$2V = 57° \pm 2°$, positive.

$D_{22°} = 3.99 \pm 0.02$.

These refractive indices are rather higher than those usually recorded, although not quite as high as those found by Goddard and Glass (1940, p. 398), and Söhnge (1945) for optically negative allanite from near Jamestown, Colorado, and the Zaaiplaats tin mine, Transvaal, respectively. A positive optic sign has been recorded for Wilmot Pass allanite and this appears to be unusual for this mineral, since few optically positive allanites have been recorded previously (Goddard and Glass, 1940, p. 398; Kostov, 1940; and Geijer, 1927, for Mg-orthite).

AGE OF THE ALLANITE

The exceedingly low figure that has been obtained for lead in the Wilmot Pass allanite, less than 0.01 per cent, is of interest and would appear to suggest a very late origin indeed. However, the writer wishes to record the following points that appear to be relevant in this connection but at the same time it must be understood that the information to hand is probably insufficient to reconcile these data adequately.

(1) The allanite is perfectly fresh and unaltered, and no recognizable transition towards a metamict state appears to have taken place; therefore it is thought that little or no loss of radiogenic lead has occurred.

(2) Present knowledge leads one to believe that granitic intrusions of southwestern New Zealand[1] may have been emplaced some time in the late Paleozoic. In the Manapouri—Doubtful Sound area, the granitic rocks are in places mantled by mid-Tertiary arkoses, sandstones, and conglomerates, and heavy mineral residues prepared from these sediments contain notable amounts of allanite.

(3) The amount of lead is too small to allow any worthwhile age determination to be made but it should be realized that if 0.01 per cent had been the actual lead content, and it would appear to be distinctly less than this figure, the age of the mineral would not exceed 14-15 x 10^6 years, assuming all of the lead to be derived from thorium.

[1] For a detailed discussion of the possible age of the granitic and associated rocks of this area the reader is referred to F. J. Turner (1937, pp. 244-248).

This figure is clearly not in accord with the known stratigraphic relationships of the granites as they are understood at present, and it is therefore suggested, but with some hesitation, that this discord of facts may be the result of the following conditions, *viz.* very late recrystallization and redistribution of original pegmatitic allanite by aqueous solutions acting along the old pegmatite channels. This mechanism would require for allanite the kind of mobility so well shown by members of the clinozoisite—epidote series (Flett and Hill, 1912; Eskola, 1932; Turner, 1948), and particularly for the yellow ferruginous members.

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School of Mineral Sciences
Stanford University,
California.

[American Journal of Science, Vol. 249, March, 1951, Pp. 215-223]

HIGH SEA LEVELS OF THE SONORAN SHORE

RONALD L. IVES

ABSTRACT. Elevated shorelines, tombolo bars, shell banks, and widely distributed marine shells high above present sea level along the Sonoran shore of the Gulf of California indicate former existence of two or more high sea levels. Present evidence suggests that the older high sea level was approximately 115 feet above that at present; and a younger level at about 75 feet above the present.

INTRODUCTION

Preliminary Statement.—Observation, in 1931, that some of the more recent lavas in the Pinacate lava field, of Sonora, Mexico, had an "exploded" appearance, as though they had flowed into water, led to a series of field investigations, to locate this supposed body of water. Field studies disclosed that the Pinacate lava field was not submerged as a whole during the extrusion of the later lavas, but in the course of these studies considerable evidence of former elevations of sea level along the Sonoran shore was discovered.

Location and Accessibility.—The Sonoran Shore, as here defined, consists of the eastern shore of the Gulf of California, roughly between the Rio de la Concepcion and Puerto Isabel. Geographical location of the area is shown in figure 1. The map area (fig. 2) extends from the Gulf of California, across the Mexican State of Sonora, and into the State of Arizona.

The Sonoran shore, until recently, was virtually inaccessible. With the completion, in 1945, of a military highway from Ajo, Arizona, to Puerto Peñasco, Sonora (fig. 2), and of the Sonoran Railroad (Ferrocarril Intercalifornia del Sur) in 1949, parts of the shore are easily reached. Jeep trails parallel the railroad right-of-way in most places, and parts of the beach can be navigated, at low tide, by a jeep, using four-wheel drive and "low-low". Foot travel is still the best means of reaching most locations not on good trails.

Climate and Weather.—The Sonoran shore is a part of the Sonoran Desert region, one of the world's most arid areas. Temperatures are very high at all seasons, reaching 130°F. at times in summer, and falling below freezing only a few times

in a generation. Rainfall is scanty and capricious, averaging not over five inches per year in inhabited locations such as Puerto Peñasco. Rains, when they do come, are of the cloudburst type, precipitation being measurable in inches per hour. Most of the annual rainfall occurs during a few days in late summer.

Near shore, a strong land-and-sea breeze system is present, alleviating the heat somewhat. Sensible temperatures are far below indicated temperatures, because of low relative humidity. Because of high temperatures and low humidity, water needs of a man in the field are high, amounting to about two gallons a day minimum for health, and one gallon daily for survival.[1] Details of this climate, so far as they have been recorded, have been published elsewhere (Ives, 1949).

Previous Work.—Although no previous study of high sea levels in this area can be found in the literature, good geological notes on the area were taken as long ago as 1698, by Eusebio Francisco Kino, S. J. and members of his party (Bolton, 1948; Manje, 1720; Ives, 1942). More recent work includes that of Godfrey Sykes (1927), D. T. MacDougal (1908), W. T. Hornaday (1909), Carl Lumholtz (1912), and R. L. Ives (1934).

ACKNOWLEDGMENTS

During the course of this study, valuable assistance and information was received from many residents of the Sonoran area. Dependable field and historical information was given the writer by Sr. Ygnacio Quiroz, of La Cholla Bay; the late José Juan, of Quitobaquito; the late Judge Traino Quiroz, of Sonoyta; and many of the United States and Mexican Border Patrolmen, stationed at and near Sonoyta. These men on many occasions exceeded duty requirements to give information and assistance.

Deserving of special mention is Alberto Celaya, of Puerto Peñasco. Sr. Celaya, a keen observer, blessed with a phenomenal

[1] Contrary to popular superstition, the pulp of the barrel cactus, which is plentiful in this area, cannot be crushed to supply good drinking water. The resultant fluid, which has a brownish color, an aromatic odor, and the consistency of thin shellac, also has a nauseous taste, and if drunk and retained, produces deleterious physiological effects, ranging from violent catharsis to convulsions. Effects vary among individual plants and individual humans.

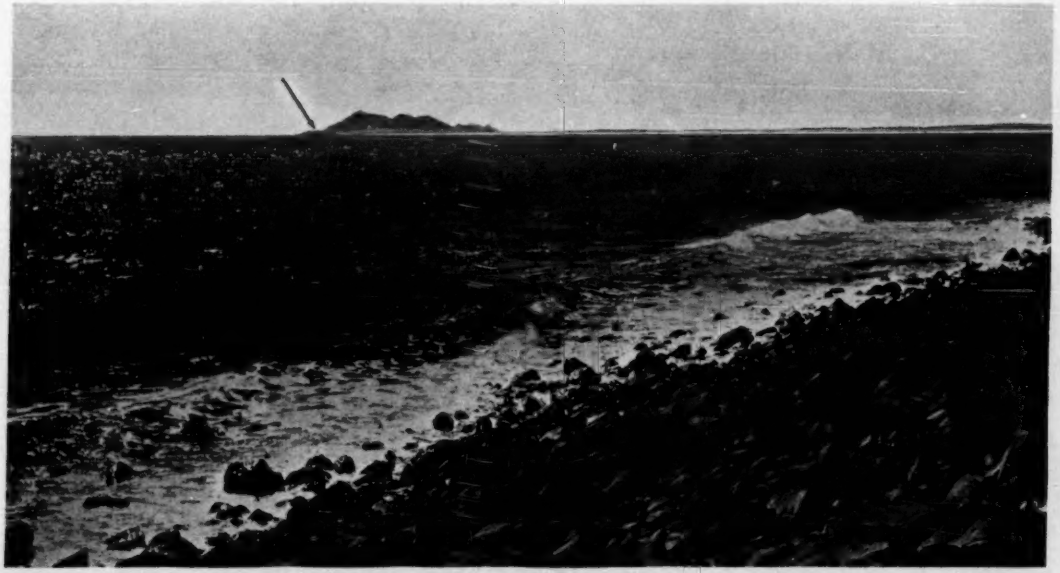

Plate 1. Shore bench and tombolo bar on Rocky Bluff, as photographed from the boulder beach at Puerto Peñasco. This bench, about 115 feet above present sea level, is cut into the seaward side of Rocky Bluff (arrow), and may be present on other sides, but is buried under deep bajada deposits and turritella-bearing sands inland. Note long low tombolo bar extending eastward from Rocky Bluff toward the mainland. Foreground water is Puerto Peñasco Bay. Rocks in foreground are basalt, eroded from the lava cap of Rocky Point, behind camera.

Plate 2. Calcareous sand matrix containing *Chione cancellata* shells from a massive deposit 75 feet above present mean sea level in the railroad cut at Puerto Peñasco.

memory and excellent judgment, assisted Carl Lumholtz during his exploration of the Pinacate region in 1909, and since that time has given help to nearly every scientific worker who has visited the area. Assistance given on numerous occasions by Sr. Celaya, and the hospitality so generously offered by his family, are here gratefully acknowledged.

NATURE AND EXTENT OF EVIDENCE

Preliminary Statement.—Data to be presented here consist primarily of scattered finds, augmented by systematic checks along the course of the Sonoran Railroad and the beaches of the Gulf of California. Although much of the evidence is here reported for the first time, a large part of it has been known to Papago *shamans* since "the time of the old ones, when God was a little boy, before Santo Cristo was born", and some of the shells figure prominently in the tribal deluge legend, as do whale vertebrae (Miocene (?) and mammoth teeth (late Pleistocene) near Quitovac (fig. 2).

Ancient Shorelines.—About the shores of the Gulf of California, roughly from Guaymas, Sonora to La Paz, Baja California, are a number of elevated shorelines, perhaps related to those on the Pacific coasts of Baja and Alta California. In the area under consideration, the major ancient shoreline is present as a bench, about 115 feet above present mean sea level, deeply incised into rocky headlands. General appearance of this bench

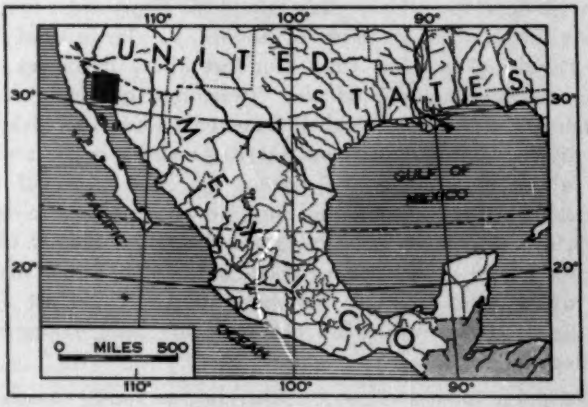

Fig. 1. Index map of Middle America, showing location of detail map area (dark shading).

is shown in plate 1. Distant from headlands, the ancient shore level is present as a discontinuous series of bar and lagoon structures, now dry, but containing extensive salt beds ("salinas," fig. 2; Lumholtz, 1912, pp. 261-265) in the ancient lagoon basins. Elevation of the former offshore bar, where it remains, is about 100 feet above present sea level; whereas the present floors of the basins are at a lower elevation, ranging from 75 to 25 feet above sea level.

Chione Cancellata Beds.—Below the shorelines, but commonly adjacent to them, and to rocky headlands, numerous deposits of calcareous sand, containing undisturbed and unaltered *Chione cancellata* shells are found. Sand components here include limestone fragments, a few heavy minerals derived from the local igneous rocks, and many shell fragments, probably derived from older deposits. Cement is a mixture of calcium carbonate and salt, so that the shells separate from their matrix in a damp climate. General appearance of this material is shown in plate 2. Sites from which substantially identical shells and matrix have been recovered are shown in figure 2.

Upper limit of the *Chione cancellata* deposits is everywhere 75 feet above present mean sea level, plus or minus 5 feet (the probable error of the aneroid in use). Because *Chione cancellata* is not a particularly good index, having a temporal range from Pleistocene to Recent, other shells, having a more limited temporal range, were searched for, but were not found.[2]

Turritella Beds.—Extending inland for many miles from the present shore, in many parts of Sonora, are large sand dunes (fig. 2), rising to more than 800 feet above mean sea level. These dunes, composed of the "sweepings of the Colorado watershed", in addition to shell fragments and other debris of local origin, contain numerous turritella shells in most places below about 300 feet above present sea level. Some of these represent modern species, and contain dried fleshy material. Others, apparently of greater age, and not specifically identifiable, have been sand-worn, or decalcified, so that they disintegrate upon being touched. Several apparently perfect specimens disintegrated into a fine powder upon being transported to a more humid climate.

[2] The writer is indebted to Dr. J. J. Galloway, for specific identification of *Chione cancellata* (Linné), and for checking other materials from the Sonoran area.

Geological significance of these shells is questionable, for they are light, and are blown many thousands of feet, even uphill, by local winds. In addition, the local gulls ("tontos", western gull) carry shellfish inland, and drop them on hard rocks to get at the meat. It is believed that these shell-bearing sands have served as an inshore "catch-all" for a long period, and hence are not representative of any one time interval or sea level regime. Relation of these turritella-bearing sands to the *Chione*

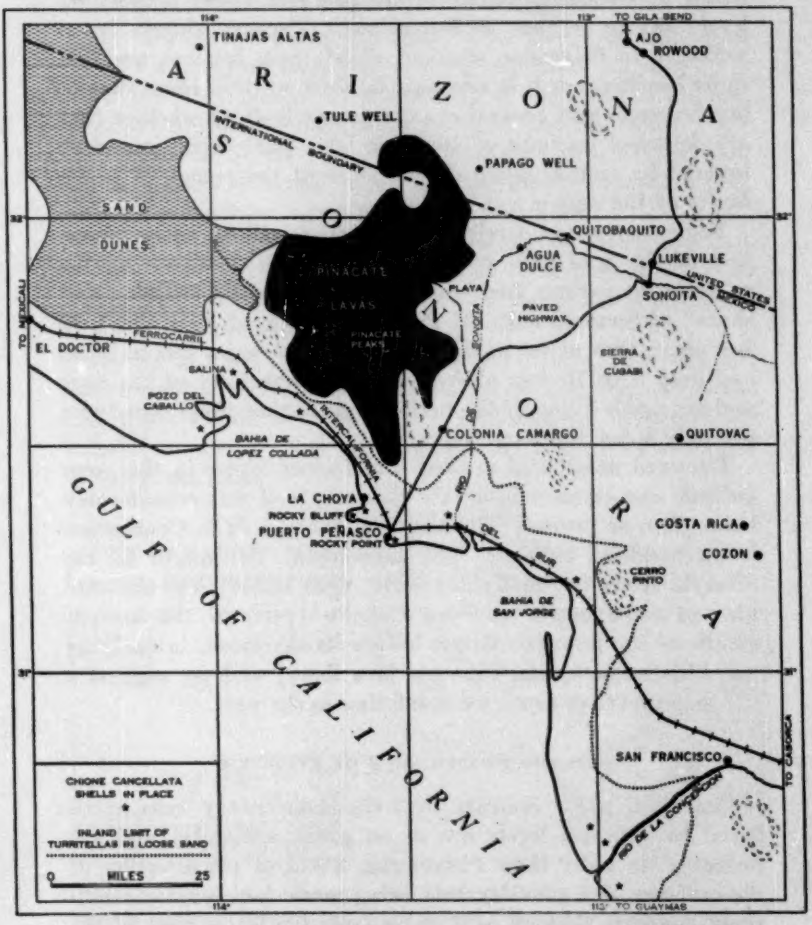

Fig. 2. Map of the Sonoran shore and ajacent areas, showing *Chione cancellata* sites, limits of turritella-bearing sand, and principal place names.

cancellata beds, the old shore bench, and the regional stratigraphy, at Rocky Bluff, is shown in figure 3. Almost identical conditions exist at Rocky Point, to the southeast.

Other Evidence.—Additional evidence that relations of land and sea were not always the same as at present along the Sonoran shore is furnished by the presence, at scattered locations, of small sectors of shore bench, cut into rocky headlands, at various elevations from 250 feet above present sea level down to perhaps 30 feet below it. Present evidence is not sufficient to determine whether all of these benches are true shore benches, nor is it adequate to show whether these various benches represent general changes in sea level, or whether they are detached portions of the main level (115 feet), raised or lowered by motion along one or more of the numerous active faults of the region.

Some evidence of a relatively recent, relatively minor, elevation of the land with respect to the sea is furnished by the presence, at various locations, particularly along the "straight shore" of Sonora, south of Puerto Peñasco, of bars about 25 feet above present sea level, with dry lagoon basins behind them, and only 5 to 10 feet above sea level. Continuity of the bars and negligible filling of the basins suggest that these structures are only a few thousand years old.

Drowned mouths of present and former rivers in this area indicate one or more intervals when sea level was considerably lower than at present. The mouth of the Rio de la Concepcion is an excellent example. The lagoons at the mouth of the Sonoyta River (normally dry below Agua Dulce), and the complex of embayments at Pozo Caballo (perhaps the ancient mouth of the Sonoyta River, before its diversion, in early or mid-Pleistocene by the Pinacate lava flows) at least suggest a rise in sea level at no very distant time in the past.

AGE AND SIGNIFICANCE OF EVIDENCE

Contained shells indicate that the sedimentary beds attributed to high sea levels are of no great antiquity, and are probably no older than Pleistocene. State of preservation of the evidence, due consideration being made for climatic conditions, suggests that all of it dates from the latter part of the Pleistocene.

The oldest feature that can be dated is the shore bench (115 foot level). This is interpreted as evidence of a rise of sea level of considerable duration. Comparison of weathering on this surface with that on similar benches in the Lake Bonneville area indicates that it is neither much older nor much younger than the Bonneville shoreline. After correcting for lack of freeze-and-thaw action in the Sonoran area, it appears that the shore bench could be dated as either Sangamon or Yarmouth, but probably is not as old as the Aftonian interglacial.

The *Chione cancellata* beds, at Rocky Bluff, are deposited not only against surfaces that are wave-scoured, but also upon debris probably created by the cutting of the shore bench, and hence are probably considerably younger than the bench. Sediments covering the *Chione cancellata* beds are typical sheetflood and bajada deposits, suggesting that the *Chione cancellata* beds were not submerged again after their formation.

The lowest, and most recent, bar and lagoon structures that are now above sea level are certainly no older than latest Wisconsin, and are plausibly attributable to the climatic optimum, of perhaps 10,000—2,000 B. C.

Dating of the turritella-bearing dune sands is purposely not attempted here, as they are believed to be long-term deposits, still in process of formation and reworking, and hence not attributable to any short-term climatic or sea level fluctuation of the Pleistocene.

POSSIBLE EXTENSIONS

In a very general way, it is possible to trace a chain of shore benches from some point south of Guaymas, Sonora to the

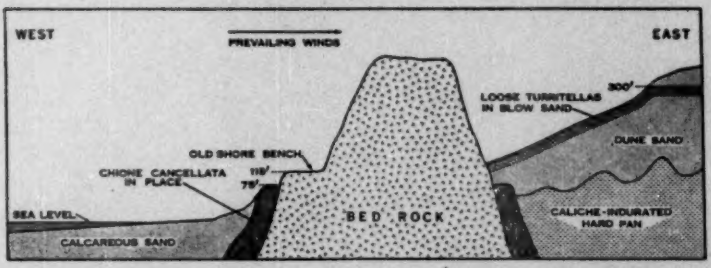

Fig. 3. Summary west-east section through Rocky Bluff, showing relations of regional bedrock, old shore bench, *Chione cancellata*-bearing deposit (which is plated around the periphyry of the older bedrock), and turritella-bearing sands.

head of the Imperial Valley, and thence southward along the shore of Baja California to Punta Final, where it can be connected with a series of elevated shorelines extending northward, with breaks, almost to Los Angeles, California.

Similarly, a high-level and a low-level bar and lagoon sequence can be found along the same course. All of this, at first glance, suggests that the sea, at least twice, stood higher than at present, with respect to the land.

In all probability, a similar chain of evidence, using the clam genus *Chione*, could also be built up.

Such an extensive regional correlation appears very plausible at first glance. If all positive evidence is cited, a very convincing case in its favor can be built up. However, if *all* pertinent evidence is used, it can only be stated that there were two or more high sea levels on the Sonoran shore, and that connection with areas nearby, also having evidence of high sea levels, is not clearly shown by the evidence.

Not shown by available evidence is that all *Chione cancellata* beds are attributable to the same rise in sea level; and that all shore benches about 115 feet above present sea level represent the same former elevation of sea level; and that all lagoon and bar formations now at the same level represent the same age.

Future correlation of the high sea levels of the Sonoran shore with those of the Imperial Valley of California, and of the Baja California shore, outlined by Hubbs and Miller (1948) seems quite probable, but present correlation is prevented by hiatuses in the evidence.

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Indiana University
Bloomington, Indiana

[American Journal of Science, Vol. 249, March, 1951, Pp. 224-248]

THE SYSTEM K_2O-MgO-SiO_2

PART 2

EDWIN WOODS ROEDDER

CRYSTALLIZATION PATHS

General.—The portion of the system above the line forsterite-$K_2O \cdot MgO \cdot SiO_2$-$K_2O \cdot SiO_2$ (*LO'G*, fig. 5) is divided into eleven sub-systems or triangles by tie lines which join the compositions of pairs of solid phases which may coexist at equilibrium at some temperature. Four of these triangular areas are ternary systems within the larger ternary system K_2O-MgO-SiO_2. In these four the compositions of the liquid phase and of all solid phases at all stages of the crystallization path of any mixture may be expressed in terms of the components at the apices of the small triangle. Four other triangles complete their crystallization paths at ternary eutectic points, but as the liquid phase from some compositions in each case leaves (and later returns to) the triangle during crystallization, or forms solid phases not representable within the triangle, they are not completely ternary. The three remaining sub-systems complete their crystallization at reaction points lying outside their triangles and hence are not ternary. These are:

Sub-system	*Ternary Reaction Point*
$K_2O \cdot 2SiO_2$-$K_2O \cdot MgO \cdot 3SiO_2$-$K_2O \cdot MgO \cdot 5SiO_2$	*B'*
Clinoenstatite-$K_2O \cdot 5MgO \cdot 12SiO_2$-$SiO_2$	*O*
Clinoenstatite-$K_2O \cdot 5MgO \cdot 12SiO_2$-Forsterite	*U*

Of these eleven sub-systems only parts of three involving the compound $K_2O \cdot 5MgO \cdot 12SiO_2$ show any complications in the crystallization paths. For this reason the part of the diagram representing the system forsterite-$K_2O \cdot MgO \cdot 5SiO_2$-$SiO_2$ has been enlarged (fig. 8) and the following discussion given. Perfect equilibrium is assumed throughout the discussion.

The Sub-system $K_2O \cdot MgO \cdot 5SiO_2$-$K_2O \cdot 5MgO \cdot 12SiO_2$-$SiO_2$. The Area SUV'.—Crystallization paths of compositions in this area are well illustrated by the actual quenching results on preparation 49 (point "*a*," fig. 8). Fifty-one quenching runs were made on this composition, which served to locate six of the eight phase changes which would occur upon crystallization or melting of this composition between the liquidus and the solidus temperatures. Table 6 gives a summary of these phase

changes. The course of this crystallization appears in figure 8 as a dotted line to show the change in composition of the liquid portion and as a dashed line to show the simultaneous change in the gross composition of the solid portion. The composition of the solids in equilibrium with any liquid occurring during the crystallization of this composition may be obtained by drawing a line from the point in question on the dotted line through the point "*a*," and extending it to its intersection with the dashed line, this intersection giving the composition of the solid phase in equilibrium with that

TABLE 6

PHASE CHANGES OCCURRING BETWEEN THE LIQUIDUS AND SOLIDUS FOR A MIXTURE OF COMPOSITION "a," FIG. 8

(See text and figures 8 and 9)

	Temperature °C	*Phases present at equilibrium*	*Composition of the liquid lies—*	*Composition of the solid lies—*
1.	>1383	All liquid	at a	none present
	at 1383		at a	at L
	1383–1283	Forsterite + liquid	along a-b'	at L
	at 1283		at b'	at L
	1283–1198	Forsterite + clinoenstatite + liquid	along b' b'''	along LK
	at 1198		at b'''	at K
	1198–1163	Clinoenstatite + liquid	along b''' -c	at K
	at 1163		at c	at K
	1163–1155	Clino + $K_2O \cdot 5MgO \cdot 12SiO_2$ + liq.	along cU	along Ku
	at 1155		at U	along uu'
	1155–1118	Forst + $K_2O \cdot 5MgO \cdot 12SiO_2$ + liq.	along Ud	along u' S
	at 1118		at d	at S
	1118–1053 ±	$K_2O \cdot 5MgO \cdot 12SiO_2$ + liq.	along de	at S
	at 1053 ±		at e	at S
2.	1053 ±–963	$K_2O \cdot 5MgO \cdot 12SiO_2$ + $K_2O \cdot MgO \cdot 5SiO_2$ + liq.	along eP	along Sp'
	at 963		at P	along p' a
	<963	$K_2O \cdot 5MgO \cdot 12SiO_2$ + $K_2O \cdot MgO \cdot 5SiO_2$ + Tridymite (no liquid)	none present	at a

1. Experimentally determined points—for data see Preparation 49 in tables 1-5.
2. Not determined directly on this composition due to the large percentage of crystals present causing experimental difficulties. Data obtained from other points listed in the tables.

liquid. For example, when the liquid has reached the point b'' (fig. 8) the solid is of the composition b, and thus consists of forsterite and clinoenstatite in the ratio of the line lengths bK and bL (i.e., 37 per cent forsterite and 63 per cent clinoenstatite). The relative amounts of this solid mixture and liquid b'' are given by the ratio of the lengths of the lines $b''a$ and ab respectively (*i.e.*, 10 per cent crystals of gross composition b and 90 per cent liquid of composition b''). With further cooling, as the liquid composition moves down $U'U$ toward U, the gross composition of the solid moves up toward K (becoming richer in clinoenstatite). When the solid portion has the composition K (all clinoenstatite), the liquid has reached b''' and the last forsterite crystal reacts with liquid to form clinoenstatite. With continued cooling the liquid changes composition along $b'''c$ while the composition of the solid remains at K, only the relative amount of solid changing (increasing). Changes on further cooling are of a similar nature and may be followed from figure 8 and table 6. The weight percentages of the various phases present in this composition throughout its cooling history have been plotted against temperature in figure 9. The abrupt changes in the amount of crystallization with slight temperature changes are noteworthy, as they are characteristic of many compositions in this area, because of the geometry of the diagram.

From table 6 and figure 8 it is seen that there are *two* different ranges of temperature over which forsterite is stable in the composition "*a*," and similar ranges exist for all other compositions in this area. Forsterite is stable, and will be present at equilibrium, from the liquidus at 1383° to 1198°, and in the range 1155° to 1118°. Between these two temperature ranges (1198° to 1155°), and below 1118°, no forsterite can exist at equilibrium in this composition.

The Area UV'V''.—Compositions in this area have crystallization paths similar to those in the area *SUV'* above, but considerably simplified. From the geometry of the diagram it is evident that none of these will cross the clinoenstatite field as above, but will travel down $U'U$ from their point of contact directly to U.

The Area UV''T'.—These possess even simpler crystallization paths, as clinoenstatite never forms, at equilibrium, during any stage in their cooling history. They merely crystallize for-

sterite until they contact the reaction line UT', follow it until all of the forsterite has reacted with liquid to form $K_2O \cdot 5MgO \cdot 12SiO_2$, and then cross the $K_2O \cdot 5MgO \cdot 12SiO_2$ field as in the previous cases.

The Sub-system Clinoenstatite-$K_2O \cdot 5MgO \cdot 12SiO_2$-Forsterite.—All compositions within this sub-system crystallize forsterite as the primary phase and then the liquid moves down the line JU' (fig. 8). Between U' and U they will leave the boundary curve and cross the clinoenstatite field if the original points lay above the line between K and U, returning to U along the reaction line TU; otherwise they follow $JU'U$ down to U. At this point crystallization is completed in all cases, the liquid reacting with the crystals of clinoenstatite to form $K_2O \cdot 5MgO \cdot 12SiO_2$ and simultaneously crystallizing forsterite and $K_2O \cdot 5MgO \cdot 12SiO_2$ directly from the liquid until the liquid is gone.

The Sub-system Forsterite-$K_2O \cdot 5MgO \cdot 12SiO_2$-$K_2O \cdot MgO \cdot 5SiO_2$.—All compositions in this sub-system complete their crystallization at point X (fig. 8). Compositions above a line between X and L (forsterite) have crystallization paths similar in general to those described for the areas SUV', $UV'V''$, and $UV''T'$ above, depending upon their location. There is one essential difference however; all of the compositions in this area which leave the forsterite-$K_2O \cdot 5MgO \cdot 12SiO_2$ reaction

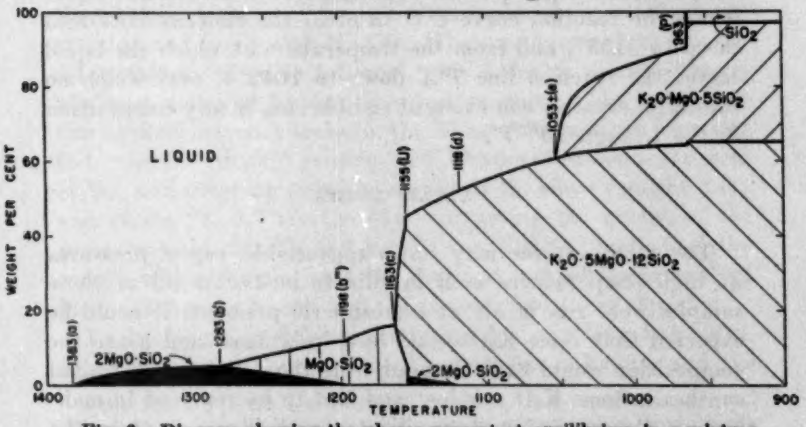


Fig. 9. Diagram showing the phases present at equilibrium in a mixture of composition "a," figure 8, between liquidus and solidus. Temperatures of phase changes obtained experimentally; percentages obtained by scaling figure 8. Letters in parentheses refer to points on figure 8 and table 6.

curve UX and cross the $K_2O \cdot 5MgO \cdot 12SiO_2$ field (all those above a line between S and X) do so only below point T' and hence contact the $K_2O \cdot 5MgO \cdot 12SiO_2$-$K_2O \cdot MgO \cdot 5SiO_2$ boundary below V, in the portion between V and X. They then proceed down VX to X.

The little triangle $XV'''V'$ in the upper part of this subsystem is particularly interesting, as compositions in this area have *three* different stability ranges for forsterite. The phase changes responsible for this have been observed on other compositions, although not all on the same one, as no batches were made exactly within this area. However, the data on other nearby points are sufficiently precise and the geometry is such that one can trace the crystallization path that would obtain for points in this triangle. In general their crystallization paths duplicate that given above for point "*a*" (see table 6) with the one exception already mentioned—they cross the $K_2O \cdot 5MgO \cdot 12SiO_2$ field below the line $T'V$, and hence reach the eutectic point X where they crystallize forsterite, it being one of the stable phases from the solidus temperature down. It is thus apparent that these compositions, in the area $SV'''V'$ have *three* stability ranges for forsterite; two of these ranges are comparable to the two given for point "*a*" above, and the third range is from the temperature of the eutectic point X (1042°) down. Separating these three ranges are two temperature ranges (from the temperature at which the liquid leaves the reaction curve $U'U$ to cross the clinoenstatite field down to 1155°, and from the temperature at which the liquid leaves the reaction line $T'X$ down to 1042°), over which no forsterite crystals can exist, at equilibrium, in any composition in the triangle $SV'''V'$.

ALKALI LOSSES

The alkali oxides may have appreciable vapor pressures at high temperatures even in silicate melts. As all of these samples were run in air at atmospheric pressure, it could be expected that some K_2O would have volatilized and hence the composition would have changed from that set by the original synthesis. Some K_2O was lost and had to be replaced in making up the potassium tetrasilicate or disilicate used in the preparation of most of the batches, but this loss seemed to be associated almost entirely with the driving off of CO_2 and

H_2O.[34] Once these were eliminated the vapor pressure of K_2O over the silicate melt was sufficiently low to be experimentally negligible,[35] as was verified by numerous weight-loss determinations. This did not hold for compositions with a K_2O:SiO_2 ratio greater than 1:2, as weight-loss determinations showed that with increase in temperature and increase in the K_2O:SiO_2 ratio from 1:2 to 1:1, alkali losses increased rapidly. This made analysis of these batches necessary, as the extremely rapid adsorption of water on crushing made such determinations inaccurate at best, and additional losses during the quenching runs could not be determined by this method due to the sample size. These analyses should have been made on the actual quench samples that were held at the liquidus temperatures, but again the sample size was prohibitive.

As a result of these difficulties the following scheme was used: (1) The liquidus was first determined with the usual procedure using small samples. (2) A larger sample, sufficient for analysis, was folded into a platinum foil envelope supported by a platinum wire, the weight of the wire and envelope being known, and put into the furnace for the same length of time and at the same temperature as the critical quenching run. (3) After quenching, this sample was cooled quickly in a desiccator and weighed rapidly without opening. This weight minus the weight of the platinum gives the sample weight. (4) The foil was carefully peeled off the glassy sample and all three—foil, wire, and sample—were placed in a platinum crucible and fused with Na_2CO_3. The usual procedure for the determination of silica followed, with a double dehydration in platinum followed by ignition and weighing. The weight of this ignited material includes the SiO_2, the platinum wire and foil, and the "R_2O_3" residue. (5) Evaporation with HF and H_2SO_4 and weighing gave the weight of the silica (weight loss) and of the "R_2O_3" residue (by subtracting the weight of the platinum). If this "R_2O_3" figure was high, a portion of the sample within the platinum foil envelope had not been dissolved in the carbonate fusion and the process had to be repeated.

Lack of time prohibited analyzing for anything but silica. Since the original composition by synthesis is known, and the

[34] See Kracek (1932) and footnotes 7 and 10. These conditions of volatility of K_2O have been used commercially to extract potash from leucite (Madorsky, 1932).

[35] J. J. Morgan (1919) showed that the vapor pressure of K_2O over leucite and orthoclase was effectively 0 at 1335°.

only significant loss during the heating is that of K_2O, the new composition can be calculated readily from the silica analysis. The data obtained thus are given in table 7. Even in the high alkali compositions these figures could be duplicated to within a few tenths of a per cent SiO_2. More accurate analyses would have no significance since other factors were involved, such as the unknown amounts of CO_2 and H_2O still present in these preparations, differences in alkali losses between the small quench run sample and the larger one for analysis, etc. A similar analysis should be made at the temperature of each critical quench run determining a phase change in any given composition, as the alkali losses during the quench run will vary with the temperature of the run. This was not done, and it can be seen in plotting the quench data that the total composition of any given batch at the temperature at which the second phase appears was definitely higher in K_2O than that shown by the analysis made at the liquidus temperature. Several silica analyses by this method were made of compositions lower in K_2O for checking purposes, the results agreeing with the composition by synthesis within the error of the analysis.

TABLE 7

CHANGE IN COMPOSITION DURING HEATING DUE TO POTASH VOLATILIZATION

(See text for method of analysis)

	Composition by synthesis			Composition by analysis			
Preparation	K_2O per cent	MgO per cent	SiO_2 per cent	K_2O per cent	MgO per cent	SiO_2 per cent	
8	36.99	15.83	47.18	32.6	17.0	50.4	
9	31.94	27.34	40.72	26.1	29.7	44.2	
18	33.09	14.16	52.75	32.3	14.3	53.4	
71	19.83	16.97	63.20	—	—	63.18	(1)
98	9.27	19.83	70.90	—	—	70.8	(1)
98	9.27	19.83	70.90	—	—	70.7	(1)
98a	9.27	19.83	70.90	—	—	70.9	(1)
118	43.03	13.00	43.97	39.6	13.8	46.6	
119	46.08	9.86	44.06	44.6	10.1	45.3	
121a	48.41	20.72	30.87	26.8	29.3	43.9	
122	54.01	11.56	34.43	41.3	14.7	44.0	
123	59.23	3.00	37.77	55.7	3.3	41.0	
128	46.78	13.12	40.10	40.0	14.8	45.2	
130	52.00	2.00	46.00	—	—	44.6	(2)
132	40.00	20.00	40.00	31.3	22.9	45.8	
133	44.07	16.95	38.98	32.5	20.5	47.0	

(1) Check analyses made to verify assumption of negligible volatilization of K_2O in such preparations as based on weight loss determinations.

(2) This anomalous result is probably due to presence of CO_2 and H_2O in the glass, as this sample had not been heated as high as the others.

X-RAY DATA

Over 200 powder-diffraction patterns of preparations in the system were made with a North American Phillips recording Geiger counter X-ray spectrometer (Carl, 1947), and over 50 with a Type 12031 photographic unit by the same manufacturer, using a Straumanis camera of 114.59 mm. diameter. All "*d*" values given are based on the latter patterns. With both of these units low-angle lines representing "*d*" values greater than about 10-12 Å are not registered and may well be present in some of the larger lattices.

From examination of these X-ray patterns, it is fairly certain that no unrecognized new phases were present in appreciable amounts on the liquidus surface[36] nor were any formed below the solidus temperatures in the system, at least within the time-temperature relations of the various crystallization histories.[37] A few patterns showed weak lines which could not be accounted for, but these were generally hygroscopic mixtures and may well have adsorbed water during the X-ray exposure. In those samples not possessing good back-reflection lines a small amount (5 to 10 per cent) of diamond dust of <20 micron size was mixed with the sample, at the suggestion of Dr. Ralph J. Holmes. This provides sharp back-reflection lines which are quite satisfactory to establish the correction factor in the Straumanis (1949) technique, and also provides a useful check on the accuracy of the measure-

TABLE 8

Accuracy of Duplication of "*d*" Values Given in Table 9, with Duplicate Samples, in Å

Approx. "d" value	5.5	4.5	4.0	2.5	1.3
$K_2O \cdot MgO \cdot SiO_2$		.010		.006	.002
$\beta K_2O \cdot MgO \cdot 3SiO_2$	.020			.006	
$\alpha K_2O \cdot MgO \cdot 3SiO_2$			.009		.001
$\beta K_2O \cdot MgO \cdot 5SiO_2$	.05*			.003	.001
$\alpha K_2O \cdot MgO \cdot 5SiO_2$	.014			.003	
$K_2O \cdot 5MgO \cdot 12SiO_2$		.01		.005	.002

* Very diffuse lines.

[36] Due to the necessarily minute amounts of crystals present in a liquidus determination sample, such samples were generally not suitable for X-ray determination.

[37] This does not apply to compositions in the high-potash portion of the system where few examples were X-rayed. See particularly footnote 49.

TABLE 9

SUMMARY OF X-RAY DATA

("d" values given in absolute Ångström units
CuK $\alpha = 1.5418$ Å units)

$K_2O \cdot MgO \cdot SiO_2$			α $K_2O \cdot MgO \cdot 3SiO_2$		β $K_2O \cdot MgO \cdot 3SiO_2$	
d	*I*	*h.k.l*	*d*	*I*	*d*	*I*
4.48	M (3)	1.1.1	4.32	VW	6.24	S
2.73	VS(1)	2.2.0	3.99	S (2)	5.42	VW
2.328	W	3.1.1	3.12	VS (1)	4.57	Sd
2.233	W	2.2.2	2.61	S (3)	4.22	S
1.934	W	4.0.0	2.491	W	3.73	VW
1.770	VW	3.3.1	2.426	W	3.56	VW
1.580	S (2)	4.2.2	2.237	Wd	3.44	VW
1.488	Wd	3.3.3-5.1.1	2.165	Md	3.21(2)	VS
1.369	W	4.4.0	1.997	W	3.10(1)	VVS
1.314	VVWd	5.3.1	1.940	Wd	2.90	VW
1.282	VVWd	4.4.2-6.0.0	1.774	W	2.85	W
1.225	W-VW	6.2.0	1.666	W	2.67(3)	S
1.119	VW	4.4.4	1.614	W	2.64	S
1.035	W	6.4.2	1.584	M	2.454	Md
.969	VVWd	8.0.0	1.559	VW	2.311	W
.943	VWd	7.3.3	1.503	M	2.253	W
.9144	VW	6.6.0-8.2.2	1.466	W	2.112	W
.8674	VVW	8.4.0	1.441	VVW	1.950	W
.826	VVWd	6.6.4	1.372	W	1.919	VVW
.791	VVWd	8.4.4	1.339	VW	1.893	M
			1.301	W	1.723	VVW
Cubic face-centered			1.260	W	1.686	W
$a_0 = 7.746 \pm 0.007$ Å			1.235	VW	1.673	VVW
(see text)			1.214	VW	1.624	VVW
			1.201	W	1.613	VVW
			1.148	VW	1.593	VVW
			1.116	VVW	1.535	VW
			1.092	VVW	1.519	VW
			1.051	VW	1.508	VVW
			1.042	VVW	1.480	W
			1.014	VW	1.441	VWd
			.9846	VW	1.408	W
			.9746	VW	1.335	VW
			.9661	VVW	1.259	VW
			.9137	VVW	1.241	VW
			.8889	VVW	1.223	VW
			.8366	VVWd		
			.8223	VVW		
			.8197	VVWd		
			.8147	VVW		
			.7977	VVW		
			.7820	VVWd		

TABLE 9 (*Continued*)

α K_2O·MgO·5SiO_2			β K_2O·MgO·5SiO_2		K_2O·5MgO·12SiO_2	
d	*I*	*h.k.l*	*d*	*I*	*d*	*I*
5.49	S (2)	2.1.1	7.68	Wd	7.12	S
3.56	VVWd	3.2.1	5.48	Md	5.54	VVW
3.35	VSd(1)	4.0.0	5.34	Sd(3)	5.13	S
3.02	VWd	4.2.0	4.71	VWd	4.43	VS
2.85	M (3)	3.3.2	3.54	VW	4.14	S
2.64	W	4.3.1-5.1.0	3.46	VW	3.74	VS
2.55	VVWd	*	3.38	VS(2)	3.53	S
2.448	VVWd	5.2.1	3.25	VS(1)	3.25	VVS(1)
2.367	W	4.4.0	3.16	VWd	2.90	VS (2)
2.286	VWd	4.3.3-5.3.0	3.00	VW	2.76	VS (3)
2.198	VVWd	*	2.94	W	2.55	S
1.819	VWVd	5.5.2-6.6.3	2.88	VW	2.456	Wd
		7.2.1	2.82	Md	2.415	Wd
1.705	Wd	6.5.1-7.3.2	2.62	Md	2.266	VWd
1.522	VWVd	7.5.2	2.51	VW	2.175	M-Wd
1.484	VWVd	8.3.3-9.1.0	2.457	VW	2.113	W
			2.351	M	2.072	VW
*Impossible lines hence probably due to impurity or collimator.			2.283	Wd	2.016	Md
			2.152	Wd	1.914	Wd
			2.077	VW	1.852	Md
			2.045	M	1.765	M-W
cubic body-centered			1.837	VW	1.731	M-W
$a_o = 13.39 \pm 0.08$ Å			1.684	VW	1.696	VW
			1.589	Wd	1.669	VW
			1.542	VWd	1.640	VVW
			1.511	VWd	1.578	W-Md
			1.471	VWd	1.533	W
			1.420	VWd	1.513	VW
			1.375	VWd	1.472	VVW
			1.344	VWd	1.451	S-Md
			1.324	Wd	1.440	VVW
			1.293	VWd	1.415	S-Md
					1.386	VWd
					1.360	W-VWd
					1.347	VWd
					1.322	S-Md
					1.291	VWd
					1.259	Wd
					1.219	Wd
					1.200	VW
					1.190	VW
					1.114	VWd
					1.104	W-Md
					1.067	VWd
					1.053	VWd
					.9925	VWd
					.9825	VWd
					.9546	VWd
					.9308	VWd
					.8585	VWd
					.8067	VWd
					.7875	VWd
					.7795	VVWd

Note: See table 8 for reproducibility of these figures. The intensities were obtained visually; abbreviations: S-strong, M-moderate, W-weak, V-very, d-diffuse. (1) (2) (3) are the three strongest lines in order of decreasing intensity. Nickel filter used throughout.

ments.[38] The Cu_{α_1}-Cu_{α_2} doublets could not be resolved, except for a few of the higher-angle lines of the compound $K_2O \cdot 5MgO \cdot 12SiO_2$, so the weighted average of the two wavelengths was used in most cases for calculation of the "*d*" values.[39]

All "*d*" values given here are in absolute Ångstrom units rather than the older *kX* units (Bragg, 1947). Only a very few weak Cu_β(?) lines were found, as a nickel filter was used throughout. An indication of the accuracy of the values for "*d*" for the various compounds given in table 9 may be obtained from the following data on the reproducibility of the "*d*" values with duplicate samples having similar history, the major controlling factor being the sharpness of the lines.

$K_2O \cdot MgO \cdot SiO_2$(?).—This compound is face-centered cubic with a cell edge a_0 of 7.746 ± .007 Å (calculated using the 6 best higher angle lines). This determination (and the "*d*" values given in table 9) was made on a sample prepared by grinding together very finely divided silica (as "Extra Bulky" Silicic Acid), $KHCO_3$, and MgO ("Extra Light") in the correct amounts, holding for 4 days at 1000°, then heating for 1 minute at an estimated 1450° in a hydrogen flame and air quenching. Another preparation containing crystals of the compound (122, table 1) was held at 1150° for one-half hour to eliminate any $K_2O \cdot MgO \cdot 3SiO_2$ crystals and air quenched; X-ray patterns of this material, containing crystals of the compound and glass, were identical with the previous patterns but showed a smaller unit cell, $a_0 = 7.705 \pm .008$ Å. Nothing is known concerning the cause of this change in lattice dimensions. There were differences in the index of refraction of the crystals in various preparations containing the compound, but reaction with the index liquids made these measurements of doubtful value. It is possible that the compound $K_2O \cdot MgO \cdot 2SiO_2$ is also involved (see footnote 49). The unit cell measurement difference was duplicatable and indicates the need of further study of the compound. If the substitution of $2Al^{+++}$ for Mg^{++} and Si^{++++} were made in $K_2O \cdot MgO \cdot SiO_2$, the result would be $K_2O \cdot Al_2O_3$. Brownmiller (1935) has found $K_2O \cdot Al_2O_3$ to be cubic with $a_0 = 7.69$ Å, and Barth (1935) has shown that it is very close to face-centered cubic and that the

[38] Ehrenberg (1926) reported the diamond a_0 (18°) to be 3.5557 ± .001 *kX* units. The value of a_0 found here, converted to *kX* units, was 3.5587 ± .0005, the sample temperatures being unmeasured (probably about 33°).

[39] The wavelengths used here are Cu_{α_1}-1.54050, Cu_α1.5418 Å.

structures of $Na_2O \cdot CaO \cdot SiO_2$, carnegieite, cristobalite, $K_2O \cdot Fe_2O_3$, and $K_2O \cdot Al_2O_3$ are all very similar. From this and the close similarity of the powder patterns it would follow that $K_2O \cdot MgO \cdot SiO_2$ and $K_2O \cdot Al_2O_3$ are probably isostructural.

$K_2O \cdot MgO \cdot 3SiO_2$.—The X-ray data on this compound show the presence of an inversion that could not be found thermally and was not obvious optically except in specially prepared samples. Although Straumanis film technique was used to obtain the "*d*" values (see fig. 11), the X-ray spectrograph charts are more suitable to illustrate this inversion and the similarity that exists between the patterns of the two modifications. Figure 10A is a reproduction of the charts obtained with the X-ray spectrograph for samples of $K_2O \cdot MgO \cdot 3SiO_2$ glass held at 1100° for the various lengths of time indicated. These records were made with a relatively rapid scanning rate (4 degrees 2θ angle per minute), using Cu radiation and a Ni filter.[40] The change from the early metastable α modification (on the left, fig. 10A, 1) to the stable β form (on the right, 5) is readily apparent, several lines disappearing and new ones forming although the structures are apparently related.

The substitution of $2Al^{+++}$ for Mg^{++} and Si^{++++} is not uncommon in silicate minerals. If this substitution were made to completion in the case of $K_2O \cdot MgO \cdot 3SiO_2$ the compound $K_2O \cdot Al_2O_3 \cdot 2SiO_2$ would be obtained. This latter compound occurs as two natural hexagonal minerals, kaliophilite (potash nepheline) and kalsilite—both of which have been synthesized experimentally, the X-ray data on the synthetic materials agreeing with that on the natural minerals (Bowen, 1917; Thugutt, 1937; Kolaczkowska, 1937; Wyart, 1947; and Rigby and Richardson, 1947)—and an additional synthetic form which is orthorhombic by X-ray but may be either uniaxial or biaxial optically and appears to be hexagonal or pseudohexagonal by crystallographic criteria.[41] Schairer (1948) has found thermal evidence indicating solid solution in $K_2O \cdot MgO \cdot 3SiO_2$ in the system K_2O-MgO-Al_2O_3-SiO_2, but the data

[40] Each curve in figure 10 represents an automatic plot of intensity of diffracted X-rays (abcissa, increasing to right) against 2θ value (ordinate, decreasing upward). A rough scale of "*d*" values in Ångströms has been substituted for the 2θ scale for comparison purposes. The intensity coordinate is only approximately linear (see Lonsdale, 1948; Alexander, Kummer and Klug, 1949).

[41] The interrelations of these forms are somewhat involved and not completely clear (Rigby and Richardson, 1947).

indicate the relationship to be more complex than that of a simple substitution series between $K_2O \cdot MgO \cdot 3SiO_2$ and $K_2O \cdot Al_2O_3 \cdot 2SiO_2$. The external form of the crystals thus obtained changed from hexagonal (pseudohexagonal?) in low-alumina preparations to some lower symmetry in higher-alumina preparations, and the liquidus temperatures for these "mixed crystals" showed a steady increase with addition of alumina up to 1358° along the join $K_2O \cdot MgO \cdot 3SiO_2$-$K_2O \cdot Al_2O_3 \cdot 2SiO_2$.[42]

The powder pattern of $\alpha K_2O \cdot MgO \cdot 3SiO_2$ (the early-formed, possibly monotropic, optically uniaxial, crystallographically pseudohexagonal crystals) is quite similar to that of kalsilite from Uganda (Bannister and Hey, 1942; Jay and Andrews, 1947; and Claringbull and Bannister, 1948) in both "*d*" values and intensities, and the pattern of $\beta K_2O \cdot MgO \cdot 3SiO_2$ (the slightly fibrous-appearing, stable modification) is similar to that of the orthorhombic, pseudohexagonal modification of $K_2O \cdot Al_2O_3 \cdot 2SiO_2$.[43]

Although the "*d*" values in each of these two pairs of compounds match quite closely throughout, except for some intensity differences to be expected from the scattering factors (the unit-cell dimensions must be practically identical), all lines in the $K_2O \cdot Al_2O_3 \cdot 2SiO_2$ patterns having counterparts in the equivalent $K_2O \cdot MgO \cdot 3SiO_2$ patterns (within the limitations imposed by the diffuse lines obtained in the latter), there are some non-systematic differences in the "*d*" values for certain lines that seem to be larger than the possible inaccuracy in measuring the $K_2O \cdot MgO \cdot 3SiO_2$ patterns would permit. This latter is not possible by strict substitution in the lattice except insofar as might be expected in an anisotropic structure

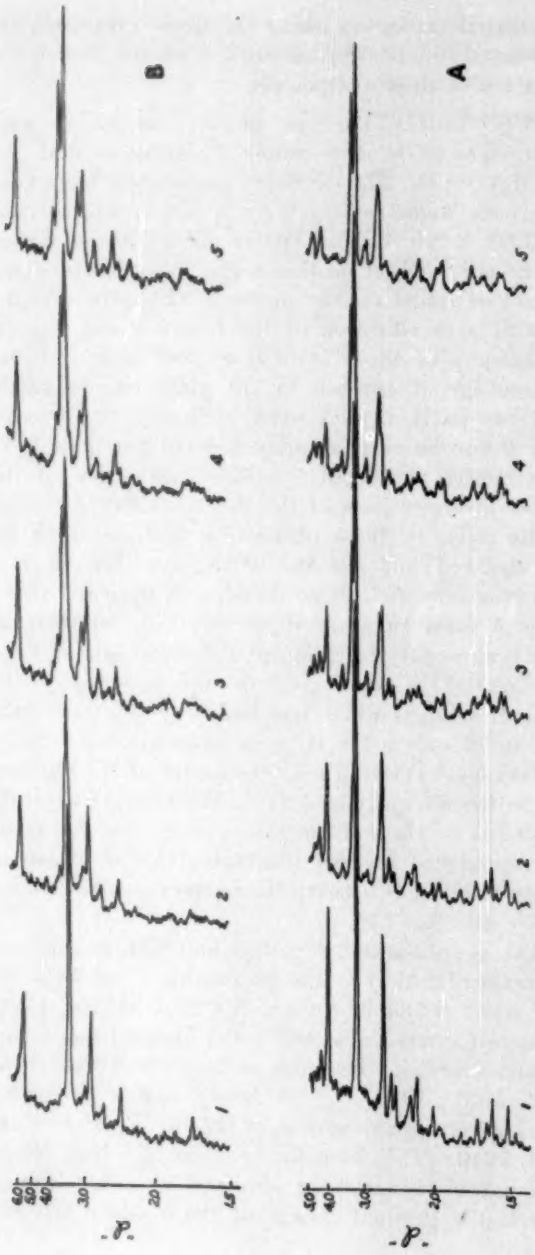
[42] Note that the melting point of pure $K_2O \cdot MgO \cdot 3SiO_2$ is only 1134°. Unfortunately the indices of refraction of the orthorhombic high-temperature form of $K_2O \cdot Al_2O_3 \cdot 2SiO_2$ are rather close to those of $K_2O \cdot MgO \cdot 3SiO_2$, making optical work difficult, and the system $K_2O \cdot MgO \cdot 3SiO_2$-$K_2O \cdot Al_2O_3 \cdot 2SiO_2$ is only partially binary at liquidus temperatures, forming leucite over a considerable range of temperatures (Schairer). X-ray powder patterns of two samples containing these mixed crystals showed a pattern identical with that of $\alpha K_2O \cdot MgO \cdot 3SiO_2$ in one case and in the other a pattern which was similar but definitely not a duplicate or mixture of that of either form.

[43] See Rigby and Richardson (1947). One would expect that the reverse of these relations would obtain—that the $\alpha K_2O \cdot MgO \cdot 3SiO_2$ pattern would be similar to that of the orthorhombic $K_2O \cdot Al_2O_3 \cdot 2SiO_2$—as the unusual combination of crystallographic and optical characters (aragonite-type pseudohexagonal twins which are strictly uniaxial optically) is so strikingly parallel in the two forms.

by differential expansion along the three axes upon substitution; obviously more detailed work is needed to determine the interrelation of these compounds.

$K_2O \cdot MgO \cdot 5SiO_2$.—There is an inversion in this compound which appears to be very similar in nature to that occurring in $K_2O \cdot MgO \cdot 3SiO_2$. The seemingly monotropic form (isotropic, early-formed, isometric crystals) is body-centered cubic with $a_0 = 13.39 \pm .08$ Å. This lattice dimension had to be determined from the 5 best medium-angle lines, for no lines above this could be found on the pattern. This was caused by the slowness of crystallization of the form; it was impossible to obtain samples of the α form free from some β form unless the percentage of crystals in the glass was so small as to make X-ray patterns very weak. Although the lines recorded in table 9 can be satisfactorily indexed for a body-centered cubic structure, it is quite possible that a few of them are really the stronger lines of the β form with "*d*" values coincidentally equal to those of possible body-centered lines due to the similarity of the two structures. Except in special samples it is very difficult to distinguish optically between the isotropic α form surrounded by strained, birefringent glass and the very weakly birefringent β form in glass. The strong line at 5.49 Å in the α pattern was practically absent in patterns of samples which had had very short crystallization (consisting of only a few large crystals in glass); in its place was a dark band starting near the center of the film and terminating rather abruptly at 5.57 Å. With longer crystallization the inversion to the β form takes place; the X-ray spectrograms reproduced in 10B illustrates this inversion and the similarity that exists between the patterns of the two modifications (see also fig. 11).

If Al_2O_3 is substituted for MgO and SiO_2 in this compound in the ratio of $2Al^{+++}$ ions for one Mg^{++} and one Si^{++++}, the end result would be leucite, $K_2O \cdot Al_2O_3 \cdot 4SiO_2$. Leucite has a well-known inversion at 600°, the higher-temperature form being isometric body-centered with $a_0 = 13.40$ Å at 625° (Wyart, 1937; 1938, O_h^{10} = Ia3d), and a low-temperature form being tetragonal with $a = 12.95$ Å and $c = 13.65$ Å (Wyart, 1940). This inversion is rapid (the high-temperature form apparently cannot be obtained at room temperature) and involves a gradual change of the *a* and *c* lattice dimen-


B
A
P.
P.

sions, a increasing and c decreasing upon heating until $a = c = 13.40$ Å at 625°. The powder pattern of the β form (more stable, birefringent) of $K_2O \cdot MgO \cdot 5SiO_2$ was found to be remarkably similar to that of the low-temperature, birefringent form of leucite both in "*d*" values and intensity. The grosser aspects of this comparison may be seen in figure 11, but the limitations of photographic reproduction of high-background films prevent showing the true degree of similarity, and exaggerate the intensity differences.

In the join clinoenstatite-$K_2O \cdot 4SiO_2$-leucite in the quaternary system K_2O-MgO-Al_2O_3-SiO_2 Schairer has found strong indications that there is a complete series of solid solutions between $K_2O \cdot MgO \cdot 5SiO_2$ and leucite with a minimum on the melting and freezing curves at the composition 6.5 per cent leucite, 93.5 per cent $K_2O \cdot MgO \cdot 5SiO_2$,[44] as might be expected in view of the similarity of the two structures.

$K_2O \cdot 5MgO \cdot 12SiO_2$.—This compound gives a pattern with many lines (fig. 11). The "*d*" values and intensities are listed in table 9. It is hoped that crystals of this compound large

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Fig. 10. X-ray "spectrograms" of powder samples of the compounds $K_2O \cdot MgO \cdot 3SiO_2$ (A), and $K_2O \cdot MgO \cdot 5SiO_2$ (B). The maxima on these curves are equivalent to the lines on a regular powder diffraction photograph, the "d" values being in Ångströms as the ordinate, and the intensity as the abcissa, increasing to the right in each curve. See text for details.

A. The compound $K_2O \cdot MgO \cdot 3SiO_2$; in each case a sample of the glass was crystallized for:

1. 3 min. at 1100°	Results: α form plus some glass
2. 1 day " "	α plus β forms, all xline
3. 2 days " "	α plus β forms, " "
4. 3 " " "	α plus β forms, " "
5. 8 " " "	β form alone, " "

B. The compound $K_2O \cdot MgO \cdot 5SiO_2$; in each case a sample of the glass was crystallized for:

1. 4½ hours at 960°	Results: Mainly α form plus some glass
2. 6½ " " "	α plus β forms " " "
3. 1 day " "	α plus β forms " " "
4. 2 days " "	α plus β forms all xline
5. 18 " " 1000*	β form alone " "

* Treatment at 960° gave a similar pattern but was not as suitable for reproduction.

[44] See Schairer (1948). There is a corollary to this in the system akermanite-gehlenite, which also has a complete series of solid solutions with a minimum near the magnesian member (akermanite) and also represents a substitution of $2Al^{+++}$ for Mg^{++} and Si^{++++}; see Osborn and Schairer (1941).

enough for rotation patterns can be isolated. No shift was found in the "*d*" values of any of the various samples containing the compound that were X-rayed, but exact measurements were not possible on the films obtained.

GEOLOGIC APPLICATION

Although, owing to the compositions involved, this system has no immediate, direct geologic application, but is essentially one of the necessary preliminaries to other investigations, there are a number of possible minor applications. Several of these have been mentioned under the headings *Introduction* and *X-ray Data* and will not be repeated here. The geochemistry of potassium has achieved considerable importance in recent years with the knowledge of its large contribution to the radioactivity of acid rocks (Hess and Roll, 1948). Variation diagrams of rock series usually show a pronounced enrichment of K_2O in the later liquids (Nockolds and Mitchell, 1948), but of course the persistence of Al_2O_3 and almost quantitative elimination of MgO by crystallization before alkali-rich liquids are obtained, as has been verified by equilibrium studies (Bowen, 1937), preclude the possibility of liquids occurring in nature with compositions approaching the system K_2O-MgO-SiO_2.

The compound $K_2O \cdot 5MgO \cdot 12SiO_2$ may well occur in natural rocks, however. Its composition (9.27 per cent K_2O, 19.83 per cent MgO, and 70.90 per cent SiO_2) and stability relationships (stable in contact with forsterite and clinoenstatite, or with clinoenstatite and silica, and probably with leucite) are such that there are many geologic environments in which it might possibly occur. The preliminary data on the quaternary system K_2O-MgO-Al_2O_3-SiO_2 as given by Schairer[45] indicate that the primary-phase volume of the compound in this quaternary system is very small; but, as no quaternary compounds are known in the system, this small phase volume does not preclude there being a large portion of the more geologically significant part of the quaternary system in which any composition must form $K_2O \cdot 5MgO \cdot 12SiO_2$ as one of its crystal phases.[46] The major

[45] Schairer, 1948.

[46] Probably most compositions in the oblique tetrahedron leucite-forsterite-silica-$K_2O \cdot MgO \cdot 5SiO_2$ within the system K_2O-MgO-Al_2O_3-SiO_2 behave in this manner, as Schairer (1948) has found the plane leucite-forsterite-silica to be truly ternary.

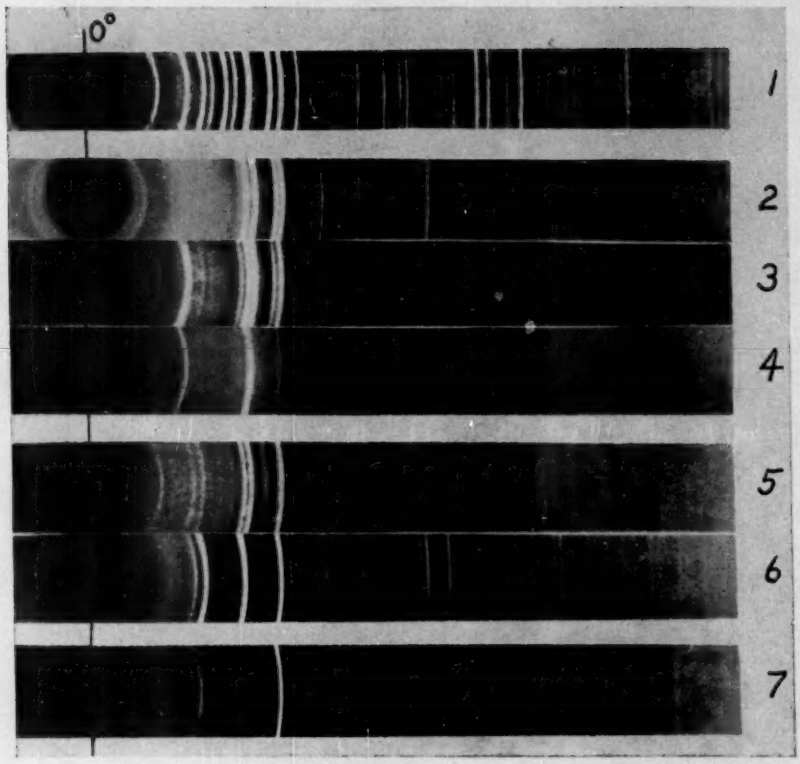

Fig. 11. X-ray powder photographs of the ternary compounds. 1. $K_2O \cdot 5MgO \cdot 12SiO_2$. 2. Leucite ($K_2O \cdot Al_2O_3 \cdot 4SiO_2$) Vesuvius (compare with 3). 3. $\beta\ K_2O \cdot MgO \cdot 5SiO_2$. 4. $\alpha\ K_2O \cdot MgO \cdot 5SiO_2$. 5. $\beta\ K_2O \cdot MgO \cdot 3SiO_2$. 6. $\alpha\ K_2O \cdot MgO \cdot 3SiO_2$. 7. $K_2O \cdot MgO \cdot SiO_2$.

obstacle in the way of the formation of the compound $K_2O \cdot 5MgO \cdot 12SiO_2$ in rocks containing the necessary potash, magnesia, and silica is the presence of water in addition to alumina. As a result of this phlogopites (essentially $K_2O \cdot 6MgO \cdot Al_2O_3 \cdot 6SiO_2 \cdot 2H_2O$) may be formed in most cases, although nothing is known of the nature of the five-component system K_2O-MgO-Al_2O_3-SiO_2-H_2O.[47] Unfortunately the optical properties of $K_2O \cdot 5MgO \cdot 12SiO_2$ are so similar to those of the quartz with which it might well be associated in nature that its discovery, if it does occur, would be difficult.

The compound $K_2O \cdot MgO \cdot 5SiO_2$ is of interest owing to its relationship to leucite ($K_2O \cdot Al_2O_3 \cdot 4SiO_2$), forming with it a complete series of solid solutions with a minimum at approximately 6.5 per cent leucite.[48] This might suggest the presence of MgO in leucites, for there are many leucite-bearing rocks containing considerable MgO, but apparently the MgO goes almost entirely to form the highly stable olivine or pyroxene lattices (Wickman, 1943). It is noteworthy that the $K_2O \cdot MgO \cdot 5SiO_2$ end of this series is stable in contact with silica while the leucite end is not, just as in the case of the olivine series (Bowen and Schairer, 1935).

The relationship of the compound $K_2O \cdot MgO \cdot 3SiO_2$ to kalsilite would likewise suggest the presence of MgO in natural kalsilites. The only analysis of kalsilite (Bannister and Hey,

[47] There have been many references in the literature to hydrothermal and dry fusion experiments synthesizing high-iron and high-flourine biotites, but iron-free, hydroxyl-bearing magnesian micas (phlogopites) have not been made. To verify the assumption that the addition of water to the system K_2O-MgO-Al_2O_3-SiO_2 will cause the formation of phlogopites in the laboratory, a mixture of the molecular composition $K_2O \cdot 6MgO \cdot Al_2O_3 \cdot 6SiO_2$ ("anhydrous phlogopite") was made and a few milligrams fused in platinum foil in an oxy-gas flame at approximately the melting point of platinum. After about 30 seconds fusion the envelope was dropped out of the flame into water 1 cm. below. The result was a glass still containing some forsterite crystals, but it had to be used anyway as this condition could not be improved. This material, finely powdered, was subjected to 15,000 psi water pressure at 900° for 1 hour in Tuttle's (1948) hydrothermal quenching apparatus. The resultant product was a very fine-grained mass which showed, in part, minute booklets of a micaceous mineral with indices of refraction in the right range and orientation for phlogopite. X-ray powder patterns of this material gave lines agreeing with those recorded for phlogopite in both intensity and position. This experiment itself shows only that phlogopite can be synthesized at that particular temperature and pressure; for the full stability relationships of phlogopite the five-component system K_2O-MgO-Al_2O_3-SiO_2-H_2O will have to be studied.

[48] Schairer, 1948.

1942) showed 3.7 per cent MgO, but much, if not all, of this was present as diopside impurity; Mügge (1927) reports only 0.15 per cent MgO in the related mineral kaliophilite from Mt. Somma.

The system illustrates several of the principles that have been advanced to explain the nature of silicate melts. The flatness of the liquidus surface over the composition of the compound $K_2O \cdot MgO \cdot 5SiO_2$ testifies to the high degree of dissociation in melts of this composition, as would be expected from the nature of the K^+ ion, and the resultant formation of Si-O polybridges or macroions (Flood and Förland, 1947; Barth and Rosenqvist, 1949) is well illustrated by the slow crystallization rates and high viscosities in this portion of the diagram. The system also illustrates the fact which Bowen (1928) has pointed out, that all the investigated silicate systems uniformly have the high melting-point material silica as one of the solid phases at a very low-temperature eutectic and at high-silica concentrations. In this system the eutectic with silica is not the lowest temperature, but close to it, and occurs at 73.5 per cent SiO_2 (point R, fig. 5).

It is interesting to note that of the compounds known to occur along the join $K_2O \cdot Al_2O_3$-SiO_2 in the system K_2O-Al_2O_3-SiO_2 (Schairer and Bowen, 1947a) 3 have counterparts in the system K_2O-MgO-SiO_2, presumably due to the substitution of $2Al^{+++}$ for Mg^{++} and Si^{++++} in each case. Thus $K_2O \cdot MgO \cdot SiO_2$ becomes $K_2O \cdot Al_2O_3$, $K_2O \cdot MgO \cdot 3SiO_2$ becomes $K_2O \cdot Al_2O_3 \cdot 2SiO_2$ (kalsilite), and $K_2O \cdot MgO \cdot 5SiO_2$ becomes $K_2O \cdot Al_2O_3 \cdot 4SiO_2$ (leucite). The compound $K_2O \cdot Al_2O_3 \cdot 6SiO_2$ (potash feldspar) and the cubic compound $K_2O \cdot Al_2O_3 \cdot SiO_2$ (Weyberg, 1908) apparently have no counterparts on the liquidus surface.[49] The increasing melting point of the series of compounds $K_2O \cdot MgO \cdot 5SiO_2$, $K_2O \cdot MgO \cdot 3SiO_2$, $K_2O \cdot MgO \cdot SiO_2$ is

[49] X-ray patterns taken recently of samples in the vicinity of point *G'* (fig. 5) show the presence of an unknown compound which may well be the cubic isomorph of $K_2O \cdot Al_2O_3 \cdot SiO_2$ (hence with the composition $K_2O \cdot MgO \cdot 2SiO_2$), but the reconnaissance nature of the data in that area precludes any more positive information at this time. This compound, whatever its composition, probably is isometric, thus explaining the observed variations in the index of refraction of crystals thought to be $K_2O \cdot MgO \cdot SiO_2$. If the above is true, the compound probably melts incongruently to form crystals of $K_2O \cdot MgO \cdot SiO_2$ and a more siliceous liquid. Its X-ray powder pattern is distinct from those of the other compounds but is not sufficiently well established to report now.

parallel to the similar increase in the series potash feldspar, leucite, kaliophilite pointed out by Wickman (1943).

The multiple recurrent crystallization of the olivine forsterite in some compositions in this system (see *Crystallization Paths*) is of interest, not in these compositions themselves, but as a process of possible petrologic occurrence. There are several ways in which the same phase may crystallize in separate temperature ranges in the cooling history of a given melt ("recurrent crystallization"). The most common is that due to a particular type of curvature of a boundary line relative to the composition points of the two crystal phases in equilibrium with liquid along it (Andersen, 1915). Another type, due to crystal fractionation, may occur in some systems involving solid solution series. The system MgO-FeO-SiO_2 is an example of this, as Bowen and Schairer (1935) have shown that with fractional crystallization of certain melts olivines (of different compositions) could form at two different stages in the cooling history, although in general olivines separate out first (Bowen, 1922). A third type occurs in the present system, in which repeated recurrent crystallization of olivine occurs during cooling, at complete equilibrium (nonfractional crystallization), its occurrence being dependent solely upon the geometry of the equilibrium diagram and the olivine formed is of uniform composition throughout. In fact, fractional crystallization would tend to prevent the occurrence of this type of recurrent crystallization, but in spite of this it is possible that similar recurrent crystallization may occur in the multicomponent systems representing actual rock magmas and may help to explain some of the irregularities that have been observed in the order of crystallization in natural rocks.

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Geophysical Laboratory
Carnegie Institution of Washington
Washington, D. C.

Department of Mineralogy
University of Utah
Salt Lake City, Utah

[American Journal of Science, Vol. 249, March, 1951, Pp. 249-253]

ON THE FALL OF THE GIRGENTI METEORITE AND ON THE KNOWN SPECIMENS OF THIS FALL

MAX H. HEY

IN the March 1950 number of this Journal, Stuart H. Perry describes two hitherto unrecorded masses, 8750 and 2151 grams, of the Girgenti meteorite. The smaller stone appears to be only about half of its original size, and Perry concludes that it is the mass of 3-4 kg. mentioned by O. Buchner in 1863, and that most of the 3389 grams of fragments listed by E. H. Wülfing were broken from it; the larger stone Perry identifies with the "pietra intera" mentioned by G. vom Rath in 1869 on the authority of Professor Gemmellaro of Palermo. Both stones were obtained by Perry from G. Bonafede of Palermo, whose uncle, S. Bonafede, received the smaller one, soon after it fell, from G. Guidice on whose farm the fall took place. S. Bonafede lent the smaller one to his friend Professor G. G. Gemmellaro, and also broke off and sold fragments of it. The larger stone Bonafede acquired later—presumably, as Perry argues, later than 1869, since Gemmellaro had no definite knowledge of it when vom Rath was inquiring at that date—and his nephew believes he had it also from Guidice.

In 1948, the British Museum purchased from R. Palumbo of Rome a 467-gram fragment (B. M. 1948, 255) of the Girgenti fall together with a contemporary memorandum, which is of special interest because it gives a clear description of the fall and because both memorandum and specimen were obtained by Palumbo from the descendants of G. Guidice, on whose farm the meteorite fell. G. vom Rath, who gave the fullest scientific description and analysis of this meteorite yet made,[1]

[1] The only other accounts (apart from mere mentions) are: (1) O. Buchner, 1863, p. 84; he gives the date and time of fall, states that the original mass was 3-4 kg. and that the main mass was then in the possession of G. G. Gemmellaro, and that it is a dense, fine-grained stone with small grains of nickel-iron.

(2) R. P. Greg, 1862, p. 538; he states that the specimen in the British Museum (B. M. 90271, 6½ grams) was given to him by Professor Gemmellaro when in Sicily in 1855, but a contemporary label in Greg's handwriting accompanying the specimen gives the date as April, 1854 and this is confirmed by the entries in the Allan-Greg catalogue. Greg says that

endeavored to obtain an account of the phenomena of fall through G. G. Gemmellaro in 1869, but without success. This hitherto unrecorded mass is a fragment approximately 3.5 x 6 x 9 cm. of an irregular shape and with but little crust; it shows prominent veining and is slightly brownish owing to slight oxidation.

Miss F. N. Smyth and Dr. F. A. Bannister have kindly translated Guidice's memorandum as follows:

At 19.30 hours on February 10th, 1853, the sky being clear and the air quite still and warm as though it were early spring, there was heard 2 miles east of Girgenti a sound resembling the firing of guns. This sound attracted the attention of the city and of a few peasants working in the neighbourhood, some of whom saw what appeared to be a column of smoke travelling obliquely from east to west. This column had the appearance of the beads in a rosary and from these beads issued loud detonations. The column passed a few metres above the head of one of these peasants and with a stronger detonation finished up on the land of Signor Gaspare Guidice da Favara. When all sounds had ceased and all appearance of smoke vanished, the peasants took courage and went to where the object had fallen to observe what it was and to identify it. They saw the ground scooped out for about half a metre, and at the bottom of the hole there were found three stones burnt on the outside. Two of these stones had the volume of a cubic palm and the shape of a parallelogram; the third of a more irregular shape weighed 2 kilos. Of the first two, one was sent to the Prince of Satriano and the other was carried to Signor Guidice, the owner of the estate on which it fell; the smallest to Dr. Nocito. The surface of these stones was burnt and was observed to be not smooth but having certain undulations resembling the finger-like impressions on the internal surface of the parietal bone. On fracture there appeared a dull-grey surface, veined, and with shining spots that in the

the specimen in Professor Gemmellaro's collection was also a fragment, about 2 lbs., and adds "if I recollect correctly, Professor Gemmellaro informed me an account had been printed in a Sicilian scientific journal." I have been unable to find this supposed account; it is not in Atti Accad. Palermo or Atti Accad. Gioenia; nor is it in the list of G. G. Gemmellaro's publications in the Royal Society Catalogue; nor does Dr. Nocito appear to have published anything.

(3) S. Meunier, 1884, pp. 196, 378, 525, gives figures of a fragment and of a thin section showing veining.

course of time rusted, thus revealing the presence of native iron. The fractured surface was found to adhere slightly to the tongue. The structure of these aerolites is not uniform, signs of fusion showing that they were the result of the union of fragments. The cleavage was probably produced by the impact suffered following a state of high temperature.

It has not yet been possible to carry out a chemical analysis. (The last sentence is in a different hand and has evidently been added later.)

It will be noticed that in respect of the time and circumstances of the fall and the number and weight of the stones this memorandum differs from the accounts hitherto available. The time is given as 19½ hours (6:30 P.M., G.M.T.), and this figure should surely replace Buchner's 1:00 P.M., which must have been cited at least thirdhand through Gemmellaro, who did not know Guidice or the peasants who actually observed the fall. According to G. Bonafede, his uncle described the fall as taking place during a storm and accompanied by a flash of light, but the memorandum states that the fall took place from a clear sky and mentions a smoke trail but no light phenomena.

The number of stones found is now definitely given as three, but the statement in the memorandum, that two of the masses were about the size of a cubic palm while the third and smallest weighed 2 kg., cannot be quite correct, for a palm is about 8 cm., which would make the two larger stones no more than about two kg. each; yet these two larger stones, which are described as "the shape of a parallelogram," are surely Perry's two.

It is very probable that the writer of the memorandum (perhaps Guidice himself) had seen only Guidice's stone, and that this was the smaller of Perry's two and originally weighed 3-4 kg.; an original size of say, 10 x 15 x 15 cm. might easily be put down as "about a cubic palm," especially if the writer is speaking from memory because the main mass of the stone had already been given to Bonafede (Gemmellaro had it as early as April 1854 according to Greg's contemporary label); the remark that it has not yet been possible to make a chemical analysis suggests that the memorandum was written quite soon after Guidice gave the stone to S. Bonafede; but Bonafede can hardly have known of the existence of the memorandum

or Gemmellaro would surely have been able to quote it in reply to vom Rath's inquiries.

According to the memorandum, one of the three stones was sent to the Prince of Satriano, Carlo Filangeri, the second to G. Guidice, and the smallest, 2 kg., to a Dr. Nocito. Guidice evidently broke off and kept a piece from his mass, this being the 467-gram British Museum specimen, (B. M. 1948, 255), but gave the main mass to S. Bonafede, and this is Perry's 2151-gram mass; the fragments broken off it by Gemmellaro and by Bonafede clearly include: the two Greg specimens, B. M. 90271 originally weighing 7.02 grams, and a 9.2-gram fragment mentioned by Buchner and listed in R. P. Greg's 1865 catalogue of his collection; the Bonn specimen of 38 grams, mentioned by vom Rath and listed by Wülfing; the 46½-gram[2] specimen mentioned by vom Rath; 29 grams at Göttingen acquired between January, 1868 and January, 1870; 9 grams at Calcutta acquired between 1865 and 1866; the 17½ grams at Vienna mentioned by Buchner; probably B. M. 46387, 73½ grams, bought of Hoseus in 1873; giving an original weight for Guidice's stone of at least 2847 grams.

Perry's larger mass, 8750 grams, was almost certainly the mass "sent to the Prince of Satriano;" S. Bonafede probably acquired it from him, and not from Guidice as supposed by his nephew, at some date later than 1869.

We still know nothing of the history of the smallest, irregularly shaped, 2-kg. mass sent to Dr. Nocito. Perhaps the Rome (1104 gram), the Berlin (489 gram), or the Paris (474 gram) specimen represents the main remaining mass of this stone.

The rest of the fragments mentioned by Wülfing, totalling 1112 grams, together with the 185 grams of fragments obtained by Perry, may have come from any or all of the three masses. The total known weight of the fall is now 14.96 kg.

[2] Perry quotes this as 16.602 grams; the figure in vom Rath's paper is not very clear, the type being imperfect or set a trifle low, but there can be no doubt it is really a 4, not a 1.

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British Museum (Natural History),
London, S. W. 7, England

REVIEWS

Petrology, Stratigraphy and Origin of the Triassic Sedimentary Rocks of Connecticut; by PAUL D. KRYNINE. Pp. 247, Bull. Conn. State Geol. and Nat. Hist. Survey, No. 73. Hartford, 1950 ($2.00).—This bulletin is primarily a detailed report on the petrology of the Triassic Newark sediments of Connecticut. It embodies both a comprehensive description of these deposits and an elaborate analysis of Newark sedimentation.

Although the stratigraphy and structure of the Newark Series have been known for some years, there has been no extensive petrographic study of these rocks. We are indebted to Krynine not only for such a study, which should serve as a model for similar studies, but for the masterly analysis of the data so obtained. Because the Newark sediments consist of conglomerates, arkoses, and related materials, the data presented by Krynine will be of interest to students of similar rocks elsewhere. The red-bed problem, the significance of detrital feldspar, the role of climate and relief in sedimentation, and similar topics are discussed by the author. The discussion of the principles used in the interpretation of the Newark sediments is illuminating. It is well documented with references to the literature, and although written nearly fifteen years ago, it still contains much that is new. Krynine has proved himself very skillful in weaving together the evidence from stratigraphy, paleontology, and petrology into one internally consistent picture of Triassic sedimentation.

It is difficult, if not impossible, to summarize the wealth of material contained in this bulletin in a brief review. Some of Krynine's conclusions which may be of general interest are that the red color is primary, that the sedimentation is wholly terrestrial—in part on alluvial fans and in part lacustrine and swamp—and despite the fact that the sediments are strongly arkosic (30 per cent average feldspar content) and decidedly red (52 per cent red), Krynine believes that the sediments were deposited under a savanna climate—a tropical humid climate characterized by a high and constant temperature (ca 80°F) and a heavy precipitation (over 50 inches) seasonally distributed, with a marked dry season.

On the whole, this bulletin is well written and well organized. There are, however, numerous minor defects. Typographical errors are common. Many of the figures, 3, 8 and 13 for example, have incomplete or inadequate legends. Other items noted by the reviewer are the scarcity of chemical data on the sediments (only one chemical analysis is given and this one is of uncertain origin), the inadequate evidence to support the author's statements on the nature and abundance of the clay minerals present, and the failure (perhaps deliberate) to use any color standards in the naming of the great variety of colors displayed by the Newark rocks.

Most of the new data presented by the author in this bulletin was derived from study of thin sections and heavy mineral residues. The results displayed should dispel any doubts as to the value of such studies. F. J. PETTIJOHN

Geochemistry; by KALERVO RANKAMA and TH. G. SAHAMA. Pp. xvi, 912. Chicago, 1950 (The University of Chicago Press, $15.00). —The authors of this monumental treatise have performed a most valuable task in providing for the first time in English an account of modern research on the chemistry of our planet. The work is, almost inevitably, divided into two sections, the first on general principles and the second on the detailed geochemistry of all the elements. The general section covers a wide field, dealing with meteorites and the cosmochemical abundance of the elements, the differentiation of the earth's crust and the rules governing the order of appearance of the elements in the solid state, the chemistry of erosion and sedimentation, the hydrosphere, atmosphere and biosphere, and the geochemical action of man. The final chapter of the general part returns to cosmochemistry and to the geochemical evolution of the earth. The special part on the detailed geochemistry of the elements is arranged in thirty-six chapters of varying length and detail.

The great strength of Rankama and Sahama's book is that it does exactly what it sets out to do, namely to marshal the facts about the chemistry of the earth and to give an impartial summary of the theories suggested to generalize the facts. Later editions may contain much new information, but it will be long before the book is superseded.

The book is on the whole well documented, though some of the minor points in the chapters on the individual elements are made without reference to any authority. At first this may seem less serious than a lack of documentation for important major conclusions. Experience, however, indicates that it is just the seemingly less important references that are the hardest to find. Within the reviewer's special field of biogeochemistry, which is admittedly peripheral to much of the subject matter of the book, the discussion is up-to-date and for the most part accurate, though one notes that a few time-honored legends, such as the excessive content of lithium in tobacco ash, are included. Occasionally different parts of the book seem to have been written at different times and are therefore somewhat inconsistent. It is very difficult to reconcile the quantitative accumulation of industrially produced CO_2 in the atmosphere which is considered in a special section on pp. 545-548 with the relatively rapid rate of photosynthetic turnover of CO_2 discussed on p. 337. The annual rate of increase in CO_2 content of the atmo-

sphere between 1900 and 1935 appears to have been of the order of 10^9 tons per annum while the photosynthetic turnover is at least 10^{10} tons, if only the atmosphere be considered. It is most unlikely that ten per cent additional CO_2 over and above that produced by respiration would accumulate passively in the atmosphere when it is well known that in artificial atmospheres, containing much more CO_2, photosynthesis is stimulated. Such criticisms of a lack of synthesis are, however, possibly unjustified as the authors in general seem to have tried to summarize existing syntheses rather than add to their number.

A more serious criticism is perhaps the very cursory treatment of energetics in the general section. The authors seem to find lattice energies and migration energies to be hurdles to be taken as unobtrusively and qualitatively as possible. This defect is related to the rather curious statement in the preface that "we did not especially try to cover papers written in other languages than in English, French and German, because in our opinion such papers are generally not addressed to the international audience." One sympathizes but one may not approve. To whomsoever a paper is ostensibly addressed, if it contains relevant material, it is the duty of anyone writing a definitive treatise to try to get at the contents of the paper, even if written in Ojibwa, Basque or Burmese. The limitation that Rankama and Sahama have allowed themselves has led them to write "Fersman also sought the ultimate causes of the distribution of the elements in their atomic structure. His research resulted in a monumental book of theoretical and applied geochemistry, written in Russian and published in 1933-39." This is the first and last that we hear of that book. It is actually imaginative, partisan, not too reliable, and rooted in energetics, in fact everything that the volume under review is not. The gist of Fersman's ideas can be obtained from papers and abstracts in translation, and more use might have been made of them. But one cannot have everything and all workers in fields remotely connected with the chemistry of the earth will find after acquiring Rankama and Sahama's *Geochemistry* that they owe a debt of gratitude to its authors.

G. E. HUTCHINSON

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Box J-20, REVERE, MASSACHUSETTS

VOL. 249 No. 8, 1951

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PAYNE & LANE, *Printers* — NEW HAVEN, CONN.